A Review of Extreme Wave Conditions in the Beaufort Sea

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A REVIEW OF EXTREME WAVE CONDITIONS IN THE BEAUFORT SEA

by

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ABSTRACT

Hodgins, D.O. 1985. A review of extreme wave conditions in the Beaufort Sea. Can. Contract. Rep. Hydrogr. Ocean Sci. 12:160 p.

The hindcast studies undertaken to provide wave data for the Beaufort Sea were reviewed. It is concluded that valuable data exist but that these data are limited by a lack of information on overwater winds, consideration of shallow water effects and information on ice and ice effects on wave generation and propagation.

RÉSUMÉ

Hodgins, D.O. 1985. A review of extreme wave conditions in the Beaufort Sea. Can. Contract. Rep. Hydrogr. Ocean Sci. 12:160 p.

On passe en revue les études de prévisions à posteriori entreprises dans le but de fournir des données sur les vagues en ce qui concerne la mer de Beaufort. On conclut que des données valables existent, mais que ces données sont limitées en raison d'un manque d'informations sur les vents à la surface de l'eau, d'un manque d'études sur les effets des eaux peu profondes et d'informations sur les glaces et les effets des glaces sur la formation et la propagation des vagues.

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1. INTRODUCTION

1.1 Purpose of the Study

At this time planning for hydrocarbon production in the Beaufort Sea is well advanced. Present schemes call for the use of fixed gravity structures to support topside facilities and the design of these structures depends to a large extent on ice and wave design criteria. Ice is considered to be the most critical environmental factor; however, the decisions on caisson or deck elevations and on sand berm stability during the open-water season also depend on knowledge of the wave climate, during both normal and extreme conditions.

In particular estimates of the 100-year return wave height and period are essential criteria. A number of wave hindcast studies have been carried out over the past decade, both by the oil industry and by government, to determine these parameters. The results are quite divergent, spanning the range from about five to more than 15 metres for significant wave height. Each hindcast was subject to a number of limitations imposed by the available data, the methods used or from a combination of both causes.

The purpose of this report is to critically review these hindcasts and to present a summary discussion of the results. This is primarily intended to put the results in the context for which they were derived, and to attempt, as far as possible, to indicate their reliability.

A number of follow-on studies into the use of measured wave data for extreme wave estimation, and into a more detailed statistical description of storm meteorology and ice conditions were undertaken by Esso Resources Canada Limited following the last major hindcast completed in 1981. Some of the results of these studies are reviewed briefly in this report as well.

Finally, longer-term research goals to improve design wave estimates in the Beaufort Sea are identified.

1.2 Beaufort Sea Extreme Wave Estimation--An Overview

Before presenting a detailed description of individual hindcasts, it is useful to point out some features of hindcasting wind waves in the Beaufort Sea which make it unique from other oceanic areas. The most obvious one is the nature of the sea ice cover (see Markham 1975, 1981). The extent of the marginal ice zone is highly variable from year to year, and there is often considerable ice in low concentrations between the permanent ice pack and the shoreline which may alter the wave growth mechanisms. Figure 1.1 shows a satellite image of this type of cover in the marginal zone. The interannual variability in ice cover affects the design of a hindcast since the probability of fetch occurrence is not controlled only by the meteorology and the fixed landforms but also independently by the ice. Thus the joint probability distributions for wave height are comprised of marginal distributions related to the occurrence of storms and to the occurrence of fetch. This assumes that the storms and the ice-controlled fetches are mutually independent, random events, and it assumes further that any fetch limitations arise only from the ice and not from the wind fields. Under certain restrictions these are reasonable assumptions in the Beaufort Sea.

The influence of wind duration cannot be neglected in

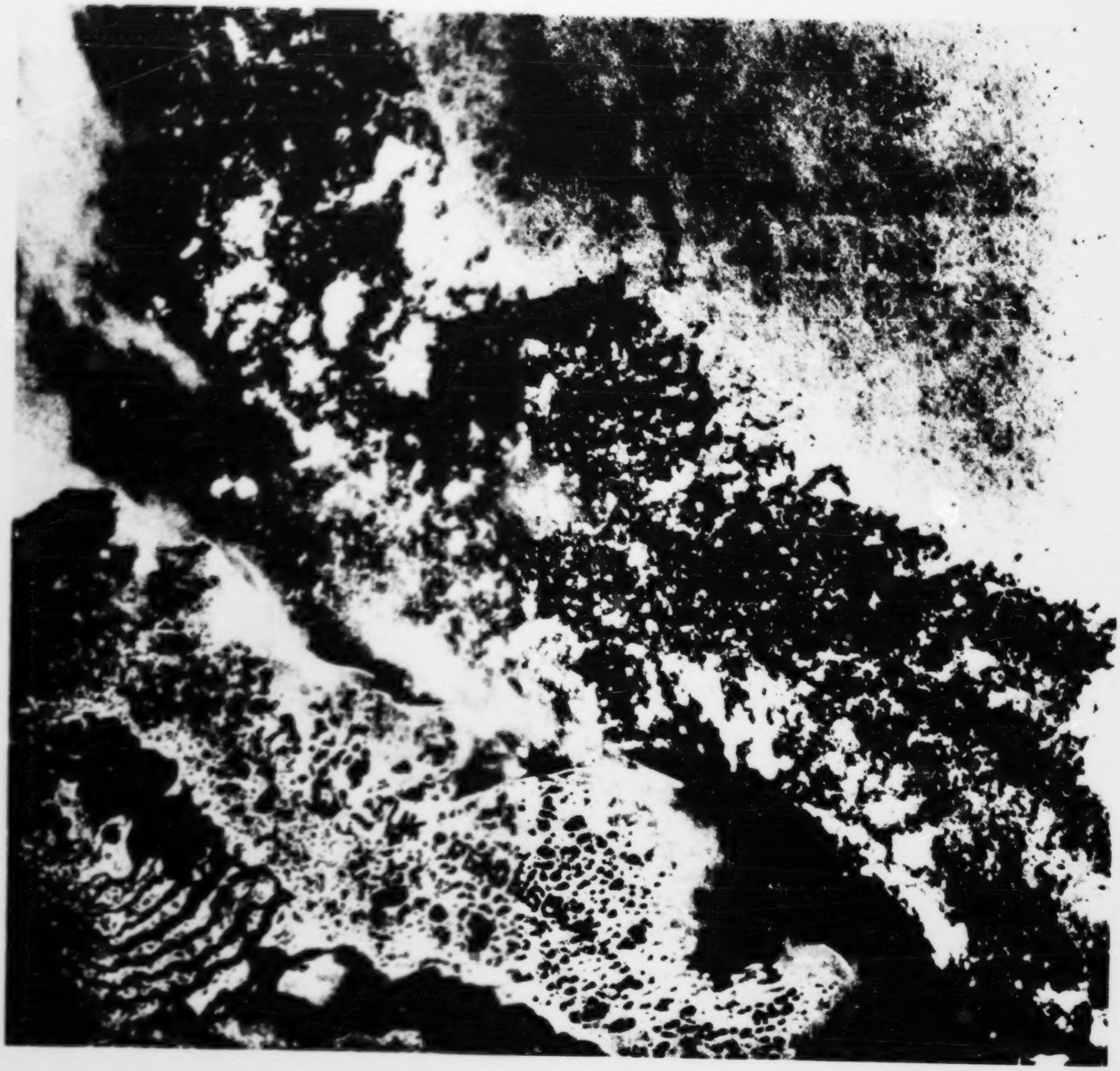


Figure 1.1 Satellite image showing large amounts of low concentration ice between the polar ice pack (upper right) and the Tuktoyaktuk peninsula (lower left).

consideration of the storms producing extreme waves. However when a design storm approach is used for the hindcast, the duration of winds can be incorporated into the measure of storm intensity for which the probability distribution is known. One can then determine extreme wave heights with a conditional probability of occurrence given certain fetch conditions.

This approach to wave hindcasting is discussed in Chapter 4; it is sufficient here to note that all hindcasts but two, the earliest done by the Institute for Storm Research (1971) and the latest done by Seaconsult (Hodgins et al., 1981) have not examined the independence of storm and fetch probabilities in deriving the 100-year wave conditions.

Two problems are presented by the low-concentration ice floes in the marginal zone. Since it is not well resolved on the existing ice data bases, it is therefore difficult to parameterize for input to a model. In addition, the influence of such ice on the physics of wave growth and decay is poorly understood. There are situations when the amount of ice might render parametric or spectral wave models invalid. However, it is very difficult to tell if and when this has happened in past hindcasts due to the number of verification trials that have been run in sufficient detail. The usual approach has been to choose an ice concentration cut-off and arbitrarily define the fetch by this ice edge definition. The sensitivity of model results to differing definitions has been examined, for example by Hodgins et al. (1982) and Baird and Hall (1980).

The principal reason for hindcasting wave heights from wind records is to take advantage of the much longer meteorological database than that available for measured waves. However, the Beaufort Sea is, meteorologically, a data sparse region and the principal sources of long term information are measured wind histories at coastal stations like Sachs Harbour, Cape Parry, Inuvik, and Tuktoyaktuk, archived surface and upper level pressure charts and the digital 381-km grid point surface pressure data. These can be used individually, or in concert, to reconstruct wind fields, and for recent years may be supplemented in Mackenzie Bay by measured winds at exploratory drilling sites. Because meteorological observation points over the open water and polar ice pack are virtually nonexistent, the confidence that can be placed in the atmospheric pressure data is lower in the Beaufort area than in pressure data along the eastern or western North American coastlines. This makes the temporal and spatial definition of fronts difficult and even the depth of central pressure in the low pressure systems uncertain, both of which impact on the accuracy of wind fields derived from the pressure data.

Quite different storm populations also appear to be present in the Beaufort Sea. Hodgins et al. (1981) have shown that, in addition to large-scale synoptic low pressure systems, there are intense localized storms, very tentatively identified as "Arctic instability lows" similar to storms found off Norway (Rabbe, 1975). They are important because they constitute a class of storms about which very little is known and which have the potential to generate severe sea-states for the Beaufort Sea. Because of their small size, perhaps 100 to 200 km in diameter, they often escape detection, or are poorly analyzed on weather charts. This makes reconstructing their wind fields difficult or impossible.

Furthermore, in most hindcasts to date there has been no attempt to distinguish annual maximum wave heights on the basis of the storms that generated them. Rather the sample maxima have been assumed to all follow the same extreme value distribution regardless of what storm type produced them. The problems associated with mixed storm populations in wave hindcasting has been addressed in a preliminary way by Resio (1978). He found that different storm types had different individual return periods and hence combining them indiscriminantly could lead to poor estimates of design wave conditions.

In summary, there are two important environmental features which make wave hindcasting the Beaufort Sea comparatively difficult: the parameterization of the sea ice and its statistical influence in extreme wave conditions, and the problems associated with recreation of overwater wind fields from sparse meteorological data.

2. PREVIOUS HINDCASTS

Five quite extensive hindcasts have been made for extreme wave conditions in the Beaufort Sea. These are identified chronologically below, together with the agency which sponsored the work:

Group or Company Executing the Hindcast	Study Date	Sponsoring Agency or Company
Institute for Storm Research (ISR)	1971	Elf Oil Exploration and Production Canada Ltd.
Intersea Research Corporation (IRC)	1974	Imperial Oil Company, Ltd.
Dames & Moore	1975	Atmospheric Environment Service
Hydrotechnology Ltd.	1980	Gulf Canada Resources Inc.
Seaconsult Marine Research Ltd.; Danish Hydraulic Institute; MEP Company	1981	Esso Resources Canada Limited

Each hindcast study is discussed in turn, concentrating on the background to the study, the data sources used, the methods followed and the key results and limitations which apply to them. This discussion is followed by an intercomparative summary of the results and a critique of the various studies. As far as possible the discussion of data sources and methods is drawn from the study reports without reading too much from between the lines. In highlighting study results, the data have been selected in such a way as to make comparison between the studies meaningful. Occasionally graphs had to be interpolated, or with somewhat more risk, extrapolated. In remarking on limitations, material extracted from the study reports has been combined with a subjective assessment of the results.

2.1 Institute for Storm Research (ISR) - 1971

This hindcast appears to be the first major effort to quantify extreme wind and wave conditions in the Beaufort Sea using a long time series of wind data compiled from surface analysis charts. It was commissioned in 1970 by Elf Oil Exploration and Production Canada Ltd. in advance of extensive offshore drilling. The Institute for Storm Research (ISR, 1971) used geostrophic wind data for the Mackenzie Bay area calculated from 31 years of surface weather charts. Four distributions of storm wind speed were derived, one for each cardinal direction. Corresponding probability distributions for fetch occurrence were then calculated from 16 years of ice chart data, and the conditional probability distributions for significant wave height were calculated by considering storm and fetch occurrence simultaneously. Extreme wave data were derived in this way for seven sites (Figure 2.1).

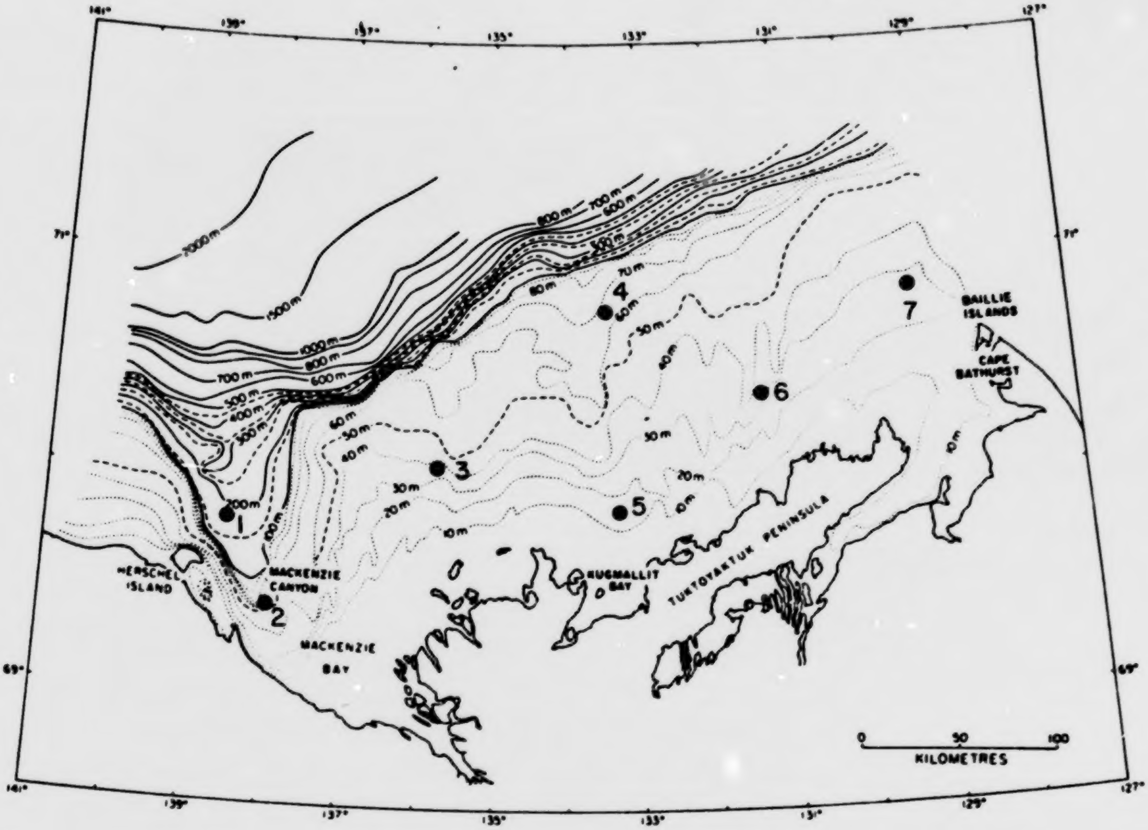
(a) Data Sources

Surface weather charts between 1939 and 1969 were used to estimate the geostrophic wind speed and direction. These charts originated from:

U.S. Weather Bureau	1939-1965
Canada Department of Transport, Meteorology Branch	1966-1969

The period from June 1 to October 31 was examined for storms on the 6-hourly charts and maximum wind speeds for each event were scaled from the papercopy charts.

Bi-monthly ice summaries prepared by the United States Navy and by Transport Canada were used to estimate



Site No.	Position	
1	69°48'N	138°31'W
2	69°20'N	138°00'W
3	70°04'N	135°47'W
4	70°47'N	133°32'W
5	69°51'N	133°22'W
6	70°24'N	131°21'W
7	70°47'N	129°15'W

Figure 2.1 Hindcast sites for the ISR-1971 hindcast study.

fetches for the months of August and September.

Observed wind data and wave height and period measurements for the period July 17 to September 12, 1970 were used to "calibrate" the wave height predictions based on geostrophic wind estimates. The wave data were measured with a Waverider buoy near Herschel Island; the wind measurements were made on Herschel Island and all data were obtained from the Department of Public Works (Canada) in 1970.

(b) Methods

The ISR-1971 report is rather vague on the precise methods they followed and so this description contains a little speculation in places; this is indicated by comments in parentheses. Nevertheless, it is possible to identify the data used and generally how they were manipulated. ISR started with a study of storms in the 31 year period from 1939 to 1969 using the 6-hourly surface weather charts. They identified three storm types:

- "fast moving storms associated with low cells,
- slow moving storms associated with low cells,
- large areas of strong winds,"

and noted that 14 major storms were found for the study period. In the next step, ISR extracted 39 geostrophic wind speed (maxima) divided among the four cardinal directions--there is no apparent connection between these data and the 14 storms--and used them to plot cumulative distributions on normal probability paper. They specified a different distribution for each cardinal wind direction. There is no discussion of wind speed or storm duration in any of this data manipulation. Using an unspecified method ISR converted these wind speed distributions into surface wind speed distributions (Figure 2.2) based on air stability considerations (no temperature data referenced).

ISR separated the fetch description from the storm analysis portion of the work. Using 16 years of bimonthly August and September chart data, the occurrence of fetches in (5-25), (25-50), (50-100), (100-200) and (>200) n.m. intervals were tabulated. This provided an estimate of the probability of fetch occurrence at a given length for each cardinal direction corresponding with the wind data treatment. An ice edge definition of five-tenths cover was used. (There is no discussion of effective fetch modifications, so we assume a straight-line projection was used.)

Deep water significant wave heights were then calculated for a matrix of wind speeds and fetch lengths ranging from 40 to 90 knots and 5 to 200 n.m. respectively. A method is not specified but the numerical values for H_s are close to those obtained using the SMB (Sverdrup-Munk-Bretschneider) equations (U.S. Army, 1977). From these significant wave heights and the probability of fetch occurrence the cumulative distribution curve for H_s was constructed. This was done for each wind direction giving curves like those shown in Figure 2.3 for sites 4 and 5 (Figure 2.1).

The deep water wave heights were modified to account for "refraction, shoaling and friction" but the method was not specified by ISR. These results are also shown in Figure 2.3 as curves marked with an appropriate significant wave period.

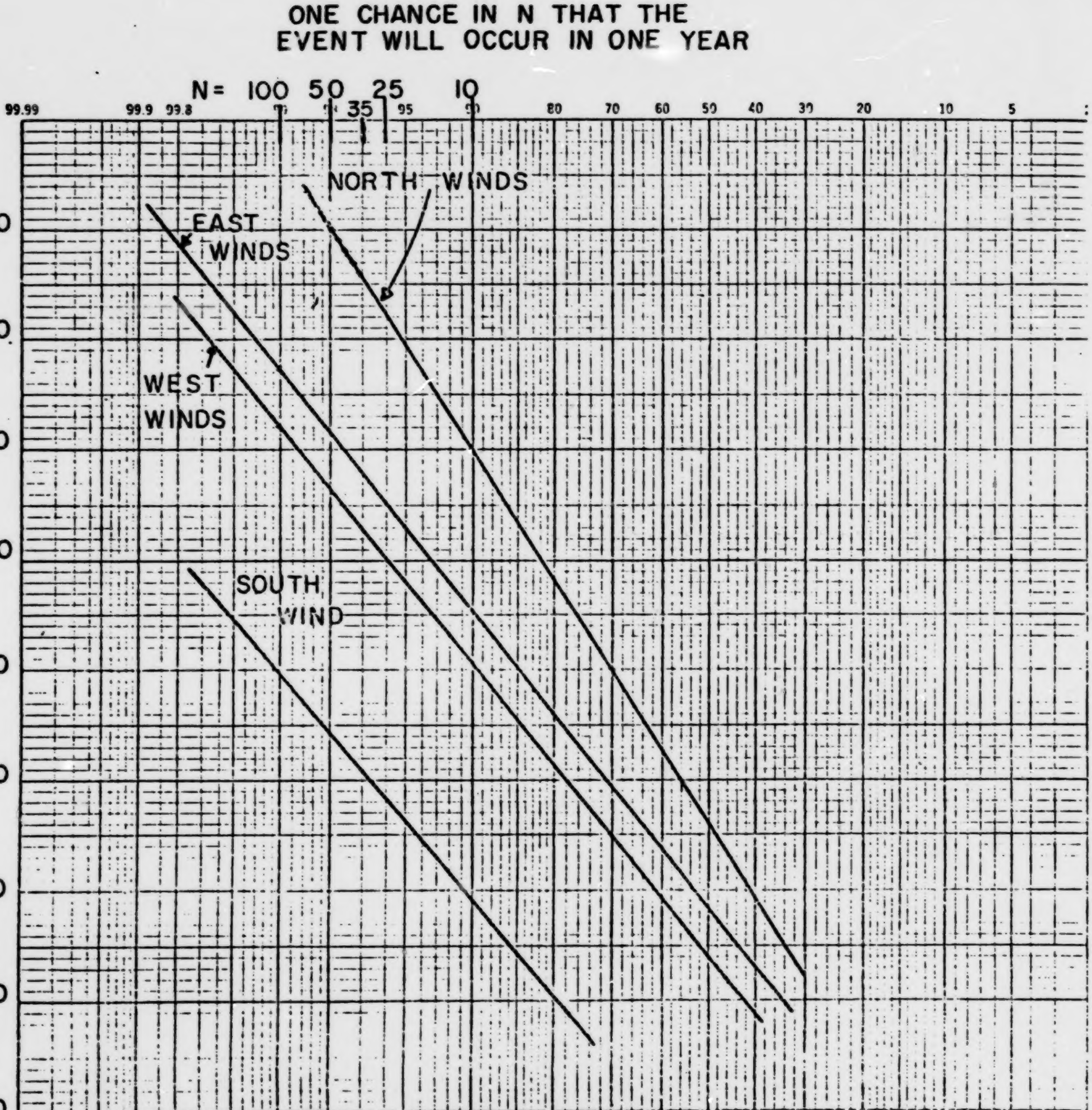
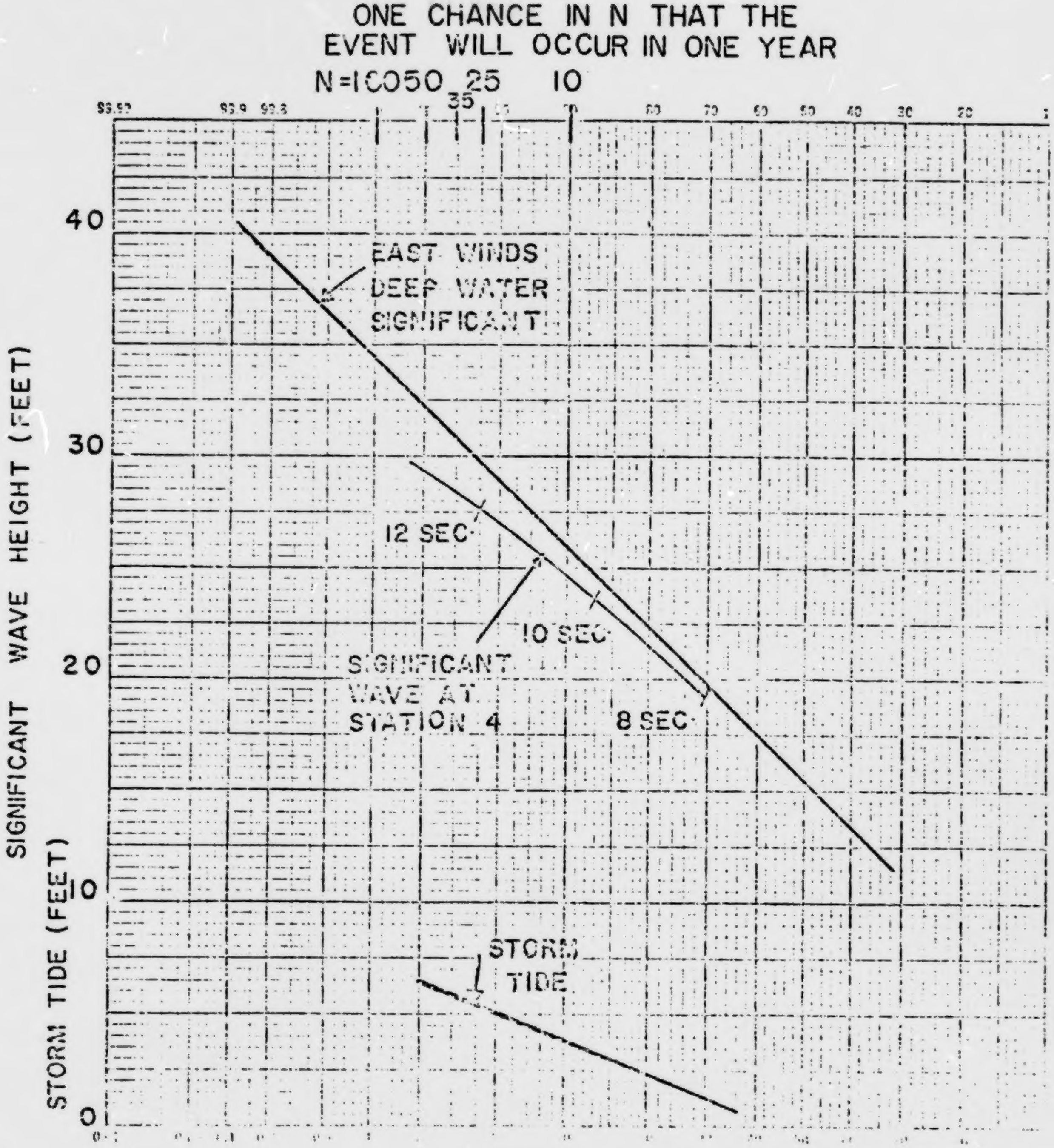
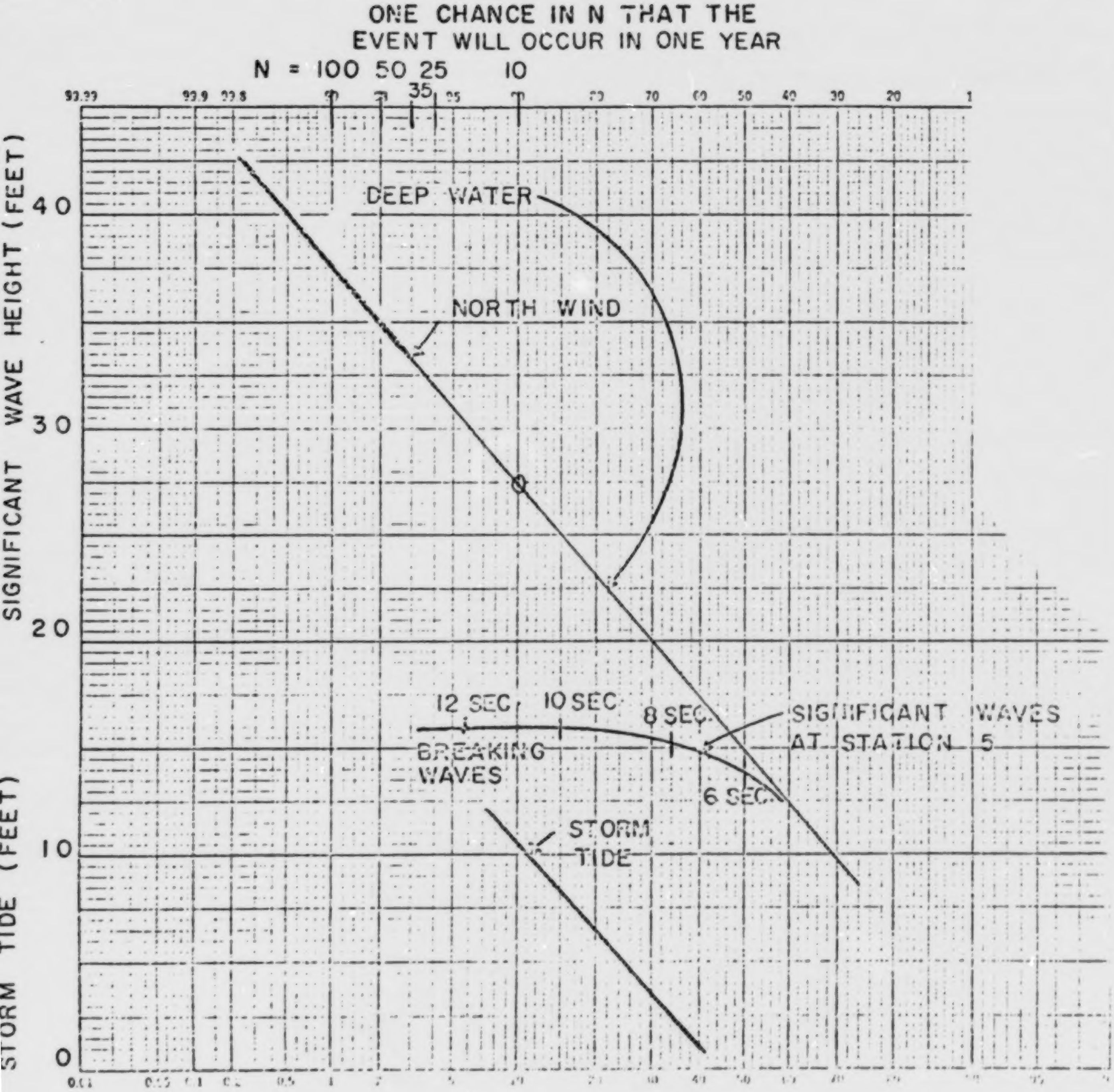


Figure 2.2 Cumulative distribution for surface wind speed, ISR-1971.



(a)

Figure 2.3 Cumulative distribution for site-specific significant wave height. (a) Site 4 - East Winds. (b) Site 5 - North Winds. (Source: ISR, 1971).



(b)

Figure 2.3 Continued.

(c) Verification Trials

From July 17 to September 12, 1970 wind and wave data were collected by the Department of Public Works (Canada) at Herschel Island. ISR used these data to make a comparison with their 12-hourly "forecast" of wind and wave parameters. This comparison is not strictly a verfication of the extreme wave procedure, but it gives some insight into how well the geostrophic winds can be scaled from weather charts, especially for the more severe storms. The comparison data are plotted as time series in Figure 2.4. Some comments are in order concerning these data:

> The significant wave heights were derived from the Waverider buoy data, but the method of calculating H_s is not mentioned.* The data are presented by ISR (1971) in one-foot increments which suggests a level of accuracy of the same order.
>
> The measured wind speed data are 3-hourly averages, to correspond with the geostrophic wind speeds (ISR, 1971).

The correspondence of measured and geostrophic winds is generally very poor. Two storms, on August 22 and 25, are smoothed out in the geostrophic analysis and the major event on September 5 is badly modelled by the geostrophic winds. In this last case, the peak wind is underestimated by about 50 percent, and a false storm is predicted on September 1.

The wave data are too limited to draw firm conclusions. However, we note that the geostrophic smoothing of the August 22 storm resulted in predicted wave heights well below measured values. Also it should be noted that due

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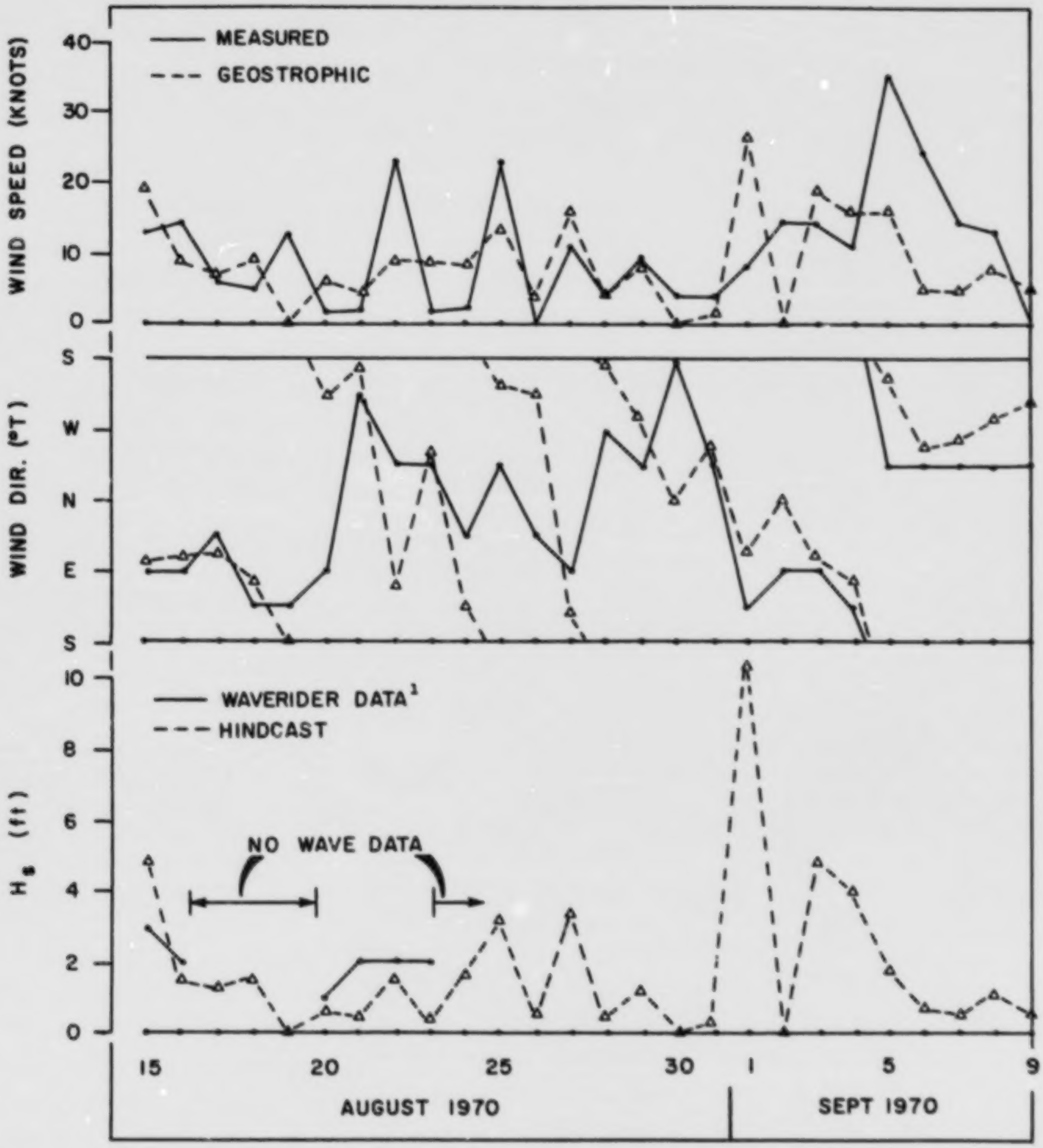
* "Note by MEDS. These data were processed by MEDS and H_s was calculated by the



[1] The method of calculating H_S from the Waverider record is not specified.

Figure 2.4 Comparison of measured wind and wave data at Herschel Island. These data were plotted from results given in ISR (1971).

to transmission difficulties with the Waverider the data are of poor quality (W.F. Baird, 1983, pers. comm.).

This comparison indicates that using surface weather maps to predict winds, which are in turn used to hindcast wave heights, is rather difficult and the resulting accuracy does not seem to be very high. As far as extreme values are concerned, the tendency for the geostrophic analysis to smooth out the wind speeds, either through inadequate temporal resolution or through systematically underestimating pressure gradients caused by poor data coverage, produces a low bias in the statistical estimates.

(d) Some Key Results

The estimated extreme values for wind speed and significant wave height at two sites, 4 and 5 as identified in Figure 2.1, are presented in Table 2.1. These sites were selected for comparison with later hindcasts and illustrate the results obtained in both deep (60 to 75 m) and shallow (~10 m) water.

(e) Limitations

The treatment of storm winds completely excludes the duration associated with the wind speed maxima. In fact it is assumed in the statistical procedures giving the extreme wave heights that wave conditions are always fetch-limited, even for fetches exceeding 100 to 200 n.m. This assumption is not justified by ISR nor supported through an examination of the data. This limits the confidence that one can place in the results.

A greater limitation is probably the reliability of the overwater winds. The comparison data discussed above

Table 2.1

Extreme wind speed and significant wave height estimates by ISR-1971.

	Return Period (Yrs)	Sites[1]					
		4			5		
		N	W	E	N	W	E
geostrophic wind speed (knots)	10	70	51	55	70	51	55
	20	79	58	63	79	58	63
	50	90	66	72	90	66	72
	100	98	72	77	98	72	77
significant wave height H_s (m)	10	7.9			5.0		
	20	8.8			5.0		
	50	9.8			5.0		
	100	10.5			5.0		

---

[1] ISR-1971 distinguished wind speeds by direction and presented extreme distributions in each cardinal direction. These values, excluding south, were scaled from ISR's (1971) graphs.

provide little confidence in the geostrophic winds derived from surface pressure charts in this area. One must also question the use of weather charts back to 1939 in view of the sparseness of recording stations in the Arctic with which to construct the early maps.

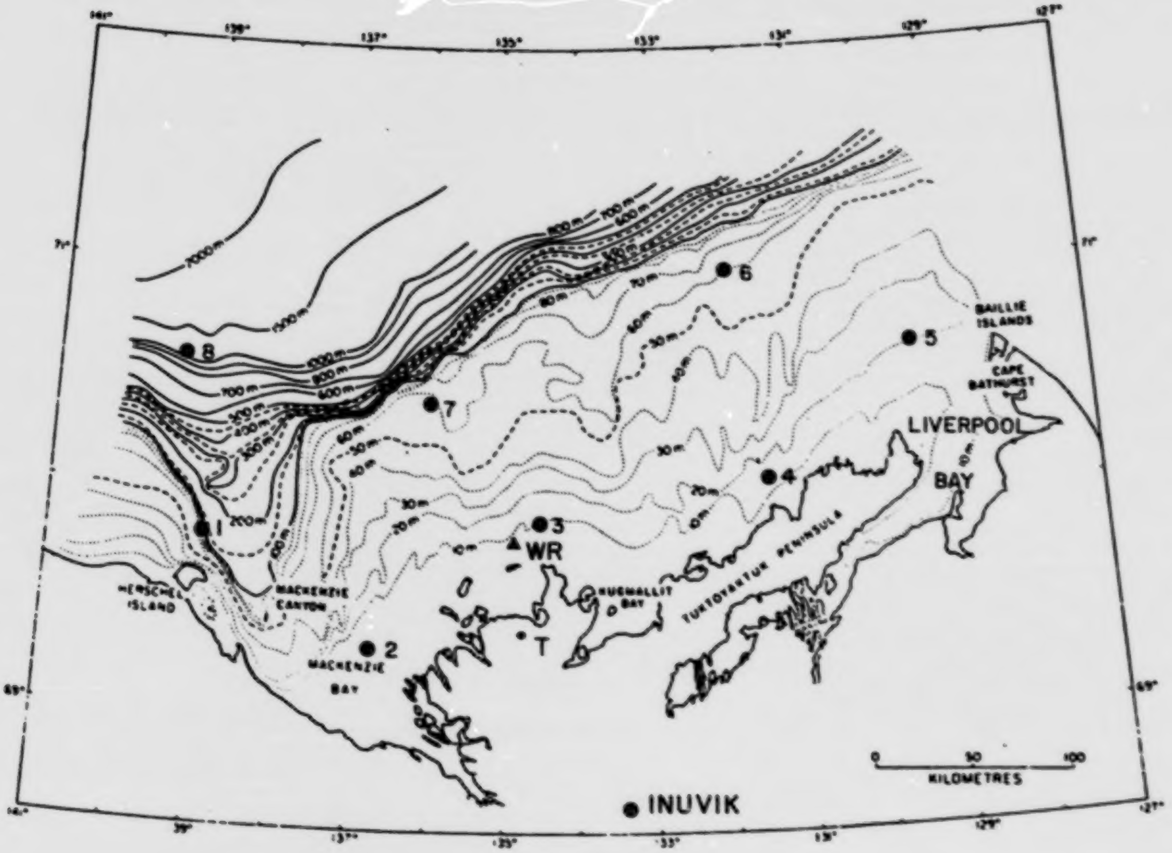
2.2 Intersea Research Corporation (IRC) - 1974

The IRC hindcast was prepared in 1974 for Imperial Oil Company, Ltd. and is available as an APOA report (APOA #70). The study compiled normal wind and wave statistics in addition to the extreme value estimates for 2, 5, 10, 20, 50 and 100-year return periods. Eight sites in the southern Beaufort Sea were examined (Figure 2.5). In the following discussion we will consider only the hindcast of extreme wave conditions.

The general approach followed was to hindcast the deep water wave conditions at each site for the "worst" storm, selected from weather charts, in each of 12 years from 1962 to 1973. The wave heights were then corrected for sheltering, shoaling and refraction and extrapolated on normal probability paper to give the required long return period values. Extreme wave periods appear to have been estimated on the basis of the wave height values.

(a) Data Sources

Winds were derived by IRC from instrumental records at Inuvik and from geostrophic winds calculated from surface pressure charts, adjusted to surface by an unspecified method. Any available ship reports were also included, and the final 6-hour wind speed and corresponding direction for hindcast purposes were obtained by blending the data by an "experienced meteorologist."



WR WAVERIDER BUOY (5027)
T TAGLU G-33

Figure 2.5 Eight hindcast sites considered by IRC-1974.

The measured winds were supplied by the Atmospheric Environment Service (AES) as were the 6-hourly weather charts. IRC (1974, p. 16) note that the Inuvik winds require scaling up by 15 percent to represent overwater winds and they have included this factor in their extremes derived from measured wind data.

Wave data for verifying the hindcast model were obtained from a Waverider deployed by Imperial Oil Company, Ltd. about 11 n.m. north of Hooper Island (Figure 2.5). Samples were 17 minutes long made nearly continuously from July 18 to September 17 and furnished estimates of significant wave height H_s and mean zero-crossing period $\overline{T}_z$. The methods of deriving these values from the records are not discussed; the calculations were done by Esso Production Research Company in Calgary.

Wind data were obtained for verification purposes from measurements at Taglu G-33 (Figure 2.5) at an elevation of 40 feet. These were used directly for input to the wave models, and were found to be the most suitable for hindcasting wave heights. Geostrophic winds derived from the 6-hourly CMC weather charts were also used.

Ice data were obtained in the form of ice charts prepared by the Ice Branch of AES. Ice-governed fetches were defined by a three-tenths cut-off value.

(b) Methods

The SMB parametric wave hindcasting procedure published by Bretschneider (1970) was used by IRC. A 6-hour average wind speed was derived for each storm and from the corresponding wind direction, a straight-line fetch between each site and the three-tenths ice edge was calculated. For high wind speeds, the fetch or the

6-hour duration was taken to limit the wave height. For lower wind speeds a slightly longer, but unspecified, duration appears to limit wave heights when the fetch exceeds about 100 n.m. (At least the results could not be reproduced using the SMB curves in the Shore Protection Manual [U.S. Army, 1977] with either of IRC's fetch or 6-hour duration.)

The deep water wave heights derived above were then corrected for:

- effective fetch
- coastline-ice sheltering
- shoaling and refraction.

Effective fetch and coastline sheltering were incorporated as a multiplicative factor $(I/I_o)^{1/2}$ on the deep water value of H_s. This factor was derived by considering the directional spread of wave energy arriving at each site using the $k(1 + \cos(2\theta))$ form proposed by Pierson et al. (1955). Essentially it approximates the total wave energy arriving at each site by the sum of a number of partial energies calculated in terms of "directional" significant wave heights spread $\pm\pi/2$ about the mean wind direction, each calculated with the appropriate fetch implied by its arrival angle at the site.

Refraction (K) and shoaling (H/H_o) coefficients were specified by methods described by CERC (1966) and combined with the sheltering coefficient as

$$K\left(\frac{I}{I_o}\right)^{1/2}\frac{H}{H_o} \qquad (2.1)$$

where

H = wave height in shallow water,
H_o = wave height in deep water,
I = wave intensity (αH_s^2) with and without subscript o to indicate deep and shallow water respectively.

Each deep water wave height was multiplied by this combined coefficient (2.1) and then by a further "ice sheltering" coefficient calculated in a similar way to the coastline sheltering factor to give the site specific storm values.

The most probable maximum wave height in 6 hours $\mu(H_{max}$ 6-hr) was then calculated at each site using Rayleigh statistics.

$$\frac{\mu(H_{max})}{H_s} = \sqrt{\frac{\ell n\ N}{2}} \qquad (2.2)$$

where

$$N = \frac{6 \times 3600}{T_s}$$

The hindcast procedure, including calculation of the ice sheltering factor, was repeated for each site for the selected storm in each of the 12 years. This yielded 12 values of H_s(1-year) which were plotted on normal probability paper and extrapolated for 20, 50 and 100-year return periods.

(c) Verification

Verification of the SMB procedures employed by IRC was attempted by hindcasting a 31-day time series of H_s measured at Waverider 5027. The results of using the geostrophic winds, and Taglu G-33 winds as directly measured, are shown in Figure 2.6. IRC (1974) do not say if the ice sheltering calculation was done for this hindcast trial but the effective fetch adjustment was made. The geostrophic wind hindcasts substantially overestimate peak wave heights. However, the Taglu wind results show generally good agreement, including most peak wave heights except on August 7 where the hindcast underestimates the peak by about 25 percent of the observed value (4.8 feet). A similar underestimate is noted on July 20 also.

IRC (1974) point out that the winds were generally light during this period and that the verification trial would have been more meaningful had waves of 8 to 10 feet significant height been measured and hindcasted.

(d) Key Results

Results from the IRC storm hindcasts from 1962 to 1973 at sites 3 and 7 are shown in Table 2.2. At site 7 the ice sheltering factors in many years produce a large reduction (20 to 30 percent) in the deep water wave heights. This in turn influences the extreme value extrapolations and raises the question of how appropriate the "effective fetch" approach is for these conditions. IRC did not verify the calculation by reproducing wave data using ice sheltering coefficients.

The extreme wind speed and significant wave height estimates are shown in Table 2.3 for sites 3 and 7.

(e) Limitations

One major limitation in this hindcast study is the lack of verification of the overwater wind characteristics

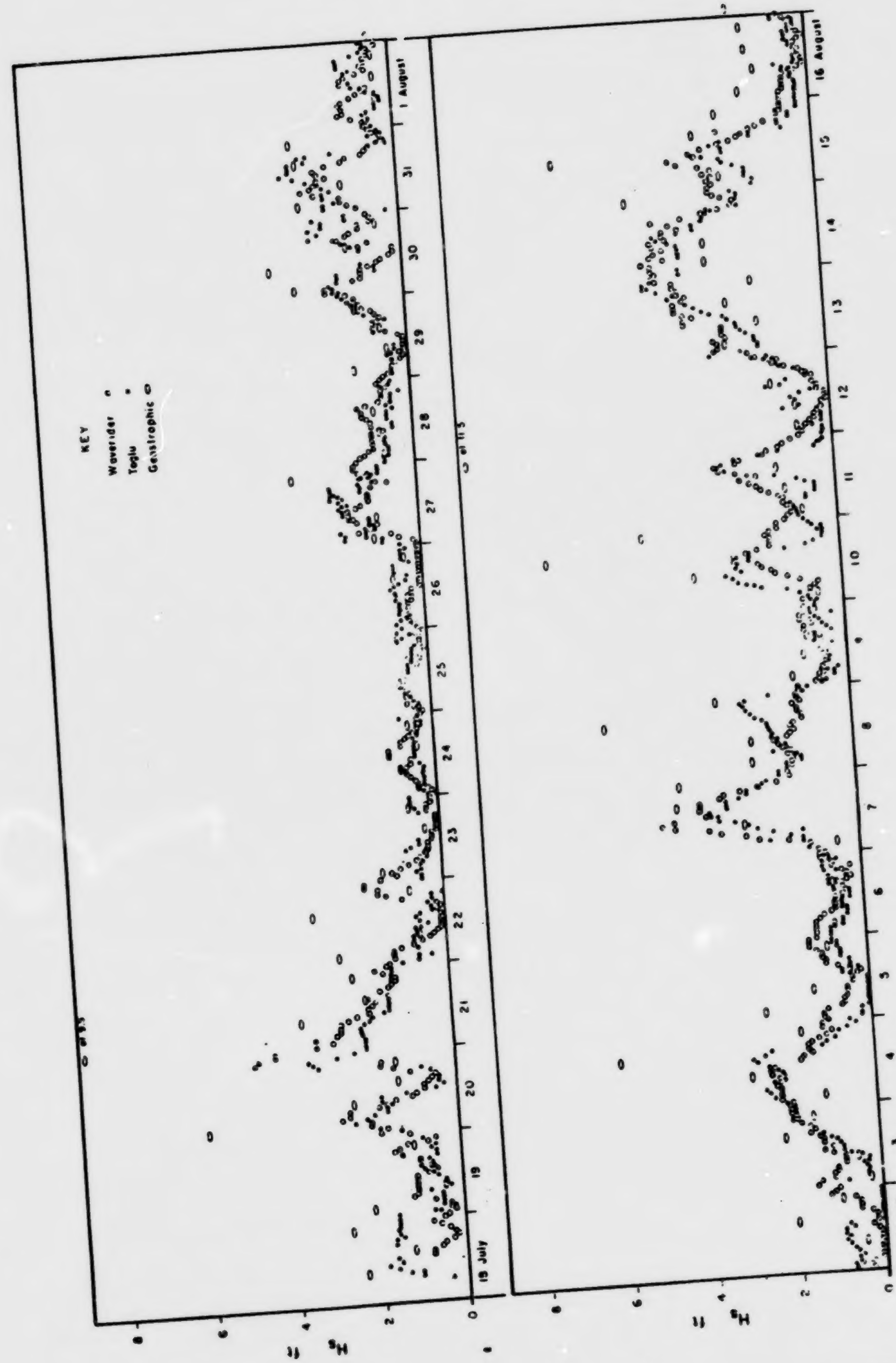


Figure 2.6 Verification trial of IRC-1974 hindcast procedure. (Source: IRC, 1974).

Table 2.2

Annual storm wave heights
calculated by IRC-1974.

Site	Year	Storm Date	Wind 6-hr Speed (kts)	Wind Dir. (°T)	Fetch (n.m.)	Deepwater H_{so} (ft)	Deepwater T_s (s)	$k(\frac{I}{I_o})^{\frac{1}{2}}\frac{H}{H_o}$	Ice Shelter Factor	H_s (ft)
3	1962	Aug. 31	35	320	80	10.1	7.0	0.91	1.0	9.2
	1963	Oct. 16	32	310	70	12.0	7.7	0.82	0.95	9.3
	1964	Sept. 4	40	310	45	11.8	7.4	0.83	0.78	7.7
	1965	Sept. 28	35	300	95	12.8	7.8	0.78	1.0	10.0
	1966	Sept. 10	30	350	20	6.6	5.6	0.91	1.0	6.0
	1967	Oct. 4	25	000	55	7.8	6.1	0.88	0.95	7.4
	1968	Sept. 7	26	310	110	9.6	6.8	0.83	1.0	7.8
	1969	Aug. 16	36	030	50	10.6	7.1	0.81	0.89	7.6
	1970	Sept. 14	44	300	140	17.0	9.0	0.74	0.92	11.6
	1971	Aug. 3	30	330	85	10.1	7.1	0.94	1.0	9.5
	1972	Sept. 2	30	320	220	14.0	8.2	0.90	0.95	12.0
	1973	Oct. 3	30	340	100	10.0	7.0	0.95	1.0	9.5
7	1962	Aug. 31	30	010	50	9.5	6.8	1.0	0.92	8.7
	1963	Oct. 16	35	310	13	6.1	5.3	1.0	0.70	4.8
	1964	Sept. 3	-	-	ice bound		-	-	-	-
	1965	Sept. 29	32	310	46	9.0	6.6	1.0	1.0	9.0
	1966	Sept. 9	18	190	70	3.8	4.3	1.0	1.0	3.8
	1967	Oct. 3	35	310	10	5.2	5.0	1.0	0.84	4.4
	1968	Sept. 7	28	310	109	9.5	6.8	1.0	0.89	8.5
	1969	Aug. 16	-	-	ice bound		-	-	-	-
	1970	Sept. 14	36	310	46	10.6	7.1	1.0	0.77	8.1
	1971	Aug. 3	30	310	36	7.7	6.0	1.0	0.77	5.9
	1972	Sept. 2	32	310	185	12.1	7.8	1.0	0.84	10.2
	1973	Oct. 3	25	340	70	7.8	6.2	1.0	0.71	5.5

Depth at Site 3 is 25 ft, and at site 7 is 190 ft.

Table 2.3

Extreme wind speed and signficant wave height estimates by IRC-1974.

	Return Period (yrs)	Site (Figure 2.5) 3	7
hourly averaged wind speed (knots)	10	41	41
	20	42	42
	50	43	43
	100	45	45
significant wave height H_s (m)	10	3.7	3.1
	20	3.7	3.4
	50	4.0	3.7
	100	4.3	4.0

for each of the 12 annual storms used to hindcast the wave heights. Thus the quality of the wind data input to the hindcast is uncertain. A second limitation concerns the annual wave height maxima at sites in deeper water which were considerably reduced in many years from the deep water significant wave height hindcast from the wind data by the "ice sheltering factor." As noted above this was calculated by a procedure generally in agreement with that recommended in the Shore Protection Manual (U.S. Army, 1977). However, later Beaufort Sea hindcasts (Baird and Hall, 1980; Hodgins et al., 1982) have shown that straight-line fetches used with the SMB procedures are verifiable even in the presence of ice. The ice sheltering factor used by IRC was not verified with measured wave data, and if as is suspected now, its application tended to reduce the deepwater wave heights too much, then the statistically extrapolated extreme values are biased low.

2.3 Dames & Moore - 1975

In 1974 AES reported on the extreme wave climatology of the Southern Beaufort Sea (AES, 1974; AES [undated]), but in evaluating this work they believed the extreme conditions to have been underestimated, particularly during "the meteorologically unstable autumn period" (Berry et al., 1975). Consequently Dames & Moore, Consulting Engineers, were contracted to hindcast wave conditions, essentially using the storm wind data derived earlier by AES. Dames & Moore (1975) reported their results to AES, which subsequently appeared in Berry et al. (1975) as Technical Report No. 21 of the Beaufort Sea Project. The Dames & Moore results were intended to replace the earlier studies undertaken by AES and, as a result, only the Dames & Moore work will be reviewed here.

The general approach was very similar to that followed by IRC-1974. Land-based winds were converted to overwater winds, fetches were determined by ice conditions for selected storms and deep water significant wave heights and periods were hindcasted using the parametric SMB method. Refraction diagrams were prepared and the deep water conditions were translated into shallow water, at standard depths, by refraction and shoaling. Extreme conditions with 10, 20 and 50-year return periods were found by extrapolating the annual maximum wave heights assuming a Fréchet (or Fisher-Tippett II) distribution using the Lieblein technique (Lieblein, 1954). The wave period associated with these design wave heights was not derived.

(a) Data Sources

Overwater winds suitable for input to the SMB method were derived from measurements at three land stations (Figure 2.7) for the given periods:

	Period
Sachs Harbour	1956-1974
Cape Parry	1959-1974
Tuktoyaktuk	1970-1974

Storm winds were defined by wind speed and duration criteria and divided into three classes by direction:

Class No.	Wind Direction (Figure 2.7)	Storm Criteria
1	WSW to NW	$U > 20$ mph
2	NNW to NNE	$D > 12$ hrs or
3	NE to ESE	$U > 35$ mph
		$D > 3$ hrs

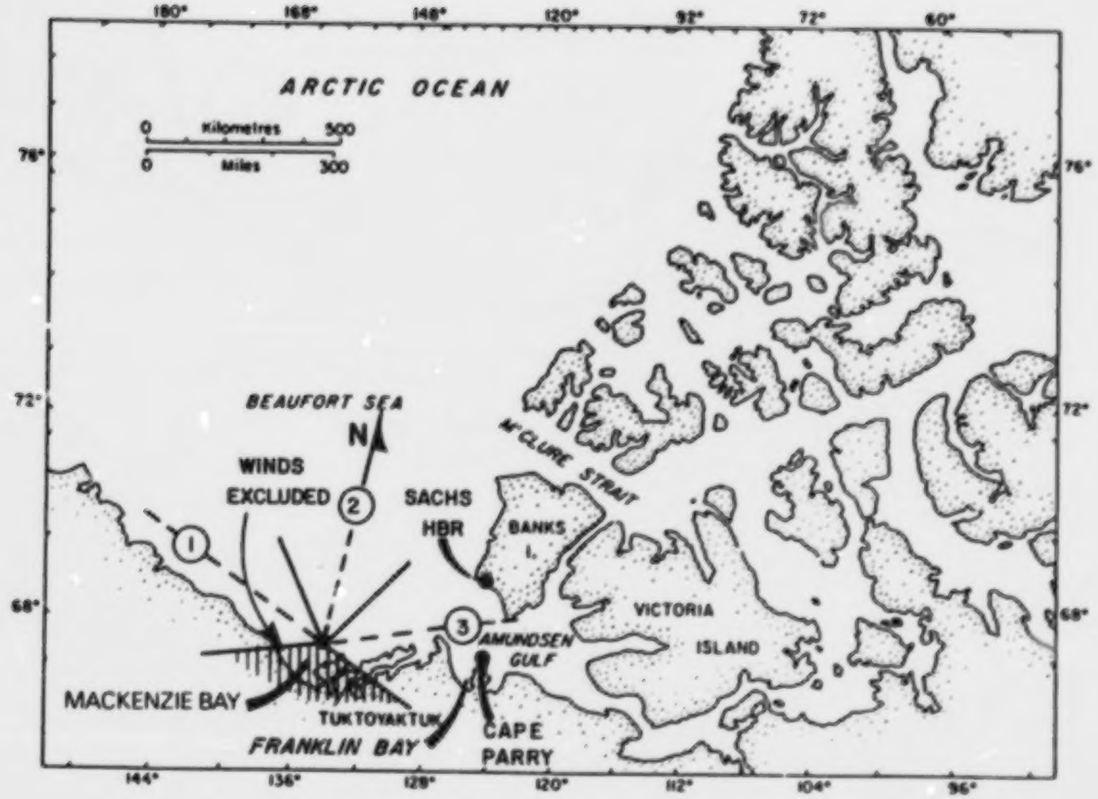


Figure 2.7 Wind measurement stations and the storm class breakdown used by Dames & Moore - 1975.

In addition, two temporal divisions were considered: July to September (called "seasonal") and July to October (called "annual") (Dames & Moore, 1975). In these criteria U is the mean (over the storm) wind speed and D is its corresponding duration; these were calculated by AES from archived data for the above stations.

Effective fetches were calculated for each storm in its class based on a straight-line projection (along the dotted lines in Figure 2.7) from the point of interest out to the appropriate ice edge. The definition of this ice edge in tenths of cover was not given by Dames & Moore (1975) or Berry et al. (1975). The sources for ice data were:

U.S. Navy hydrographic charts	1956 to 1958
Ice Forecast Central, AES	1959 to 1974

No discussion of verifying the storm selection and wind modelling procedures, nor of verifying the wave hindcasts against measurements is included in Dames & Moore (1975). Thus no data from sources independent to those already used were included in the study.

(b) Methods

Altogether 184 storms were selected between 1956 and 1974 and hindcasted using the SMB curves (U.S. Army, 1977). Overwater winds for each storm were calculated from the land-based winds using ratios determined by Lalonde and McCulloch (1975). These ratios reflect atmospheric stability, parameterized as an air-water temperature difference, based on the mean air temperature for each storm and assumed monthly mean water temperatures appropriate for each storm event.

Two sites are referred to in the Dames & Moore report, one in Franklin Bay (Figure 2.7) and one in Mackenzie Bay, more or less as situated in Figure 2.7. It is not clear from the discussion presented by the consultant, or by Berry et al. (1975), for which area, or both, fetch data were prepared for the storm-by-storm hindcast. The method of calculating effective fetch is described for a site deep in Franklin Bay--the Shore Protection Manual (U.S. Army, 1977) procedure was followed--which differs greatly from a site in central Mackenzie Bay in terms of its exposure to storm winds in each class. Nor has any rationalization between the three locations of available wind data been presented as to which is the most representative of one or the other site. It seems that one wind speed-duration pair was selected for each storm, based on unstated criteria, and that these conditions were then applied to Mackenzie and Franklin Bays uniformly.

To correct the deep water wave heights for bathymetric effects a refraction model described by Chao (1974) was run for the Southern Beaufort Sea using a regular grid with a 12.5 km spacing. To provide more detailed wave ray calculations the bathymetry data were linearly interpolated to 6.25 km.

The refraction patterns were derived for a one metre wave propagating along the central radials (dotted lines in Figure 2.7) of each storm class for 6 and 9-second waves. A sample plot for 9-second waves is shown in Figure 2.8 and the average gains for each site are shown in Table 2.4. Standard depths of 75, 50, 35, 20 and 10 metres were output from the analysis. The gain G is defined as

$$G = (K_r{}^2 + K_s{}^2)^{1/2} \qquad (2.3)$$

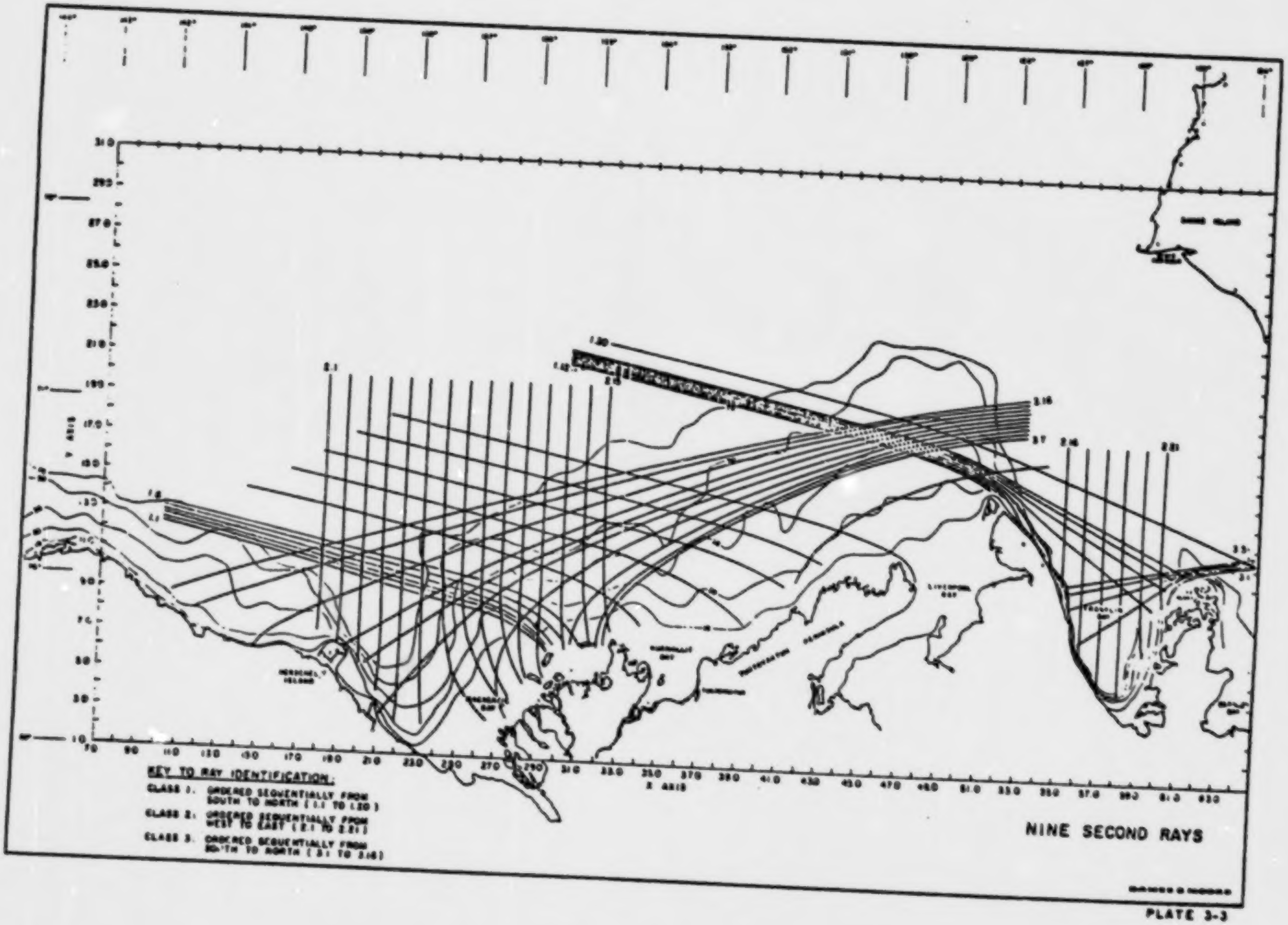

KEY TO RAY IDENTIFICATION:
CLASS 1. ORDERED SEQUENTIALLY FROM SOUTH TO NORTH (1.1 TO 1.20)
CLASS 2. ORDERED SEQUENTIALLY FROM WEST TO EAST (2.1 TO 2.21)
CLASS 3. ORDERED SEQUENTIALLY FROM SOUTH TO NORTH (3.1 TO 3.16)
NINE SECOND RAYS
X AXIS
Y AXIS
PLATE 3-3

Figure 2.8 Refraction diagrams for Mackenzie and Franklin Bays prepared by Dames & Moore (1975).

Table 2.4

Gains specified for standard depths
in Mackenzie and Franklin Bays.
Dames & Moore (1975).

CLASS	DEPTH (m)	T_{so}=6 sec		T_{so}=9 sec	
		MacKenzie Bay	Franklin Bay	MacKenzie Bay	Franklin Bay
1	75	1.0	0.99	0.81	1.0
	50	1.0	0.97	0.78	0.96
	35	0.99	0.87	0.75	0.90
	20	0.87	0.68	0.72	- *
	10	0.69	- *	0.74	- *
2	75	1.0	0.94	0.99	0.86
	50	1.0	0.92	0.96	0.86
	35	0.99	0.86	0.91	0.80
	20	0.95	0.80	0.87	- *
	10	0.89	0.67	0.95	- *
3	75	1.0	0.97	1.0	0.46
	50	1.0	0.77	0.97	0.57
	35	0.99	0.76	0.47	0.40
	20	0.22	0.67	0.44	- *
	10	0.17	0.41	0.42	- *

*Due to grid spacing of the computer model and the steep contour gradients, gain values were not obtained for some 20 and 10 metre depths.

where K_r and K_s are the refraction and shoaling coefficients respectively. Then the shallow water wave height, H_s, was calculated from

$$H_s = GH_{so} \tag{2.4}$$

H_{so} is the deep water significant wave height from the SMB hindcast.

To obtain the extreme wave heights, the shallow water wave heights at each standard depth were first calculated for each month in all 19 years of storm data using the gains in Table 2.3. Then the annual and seasonal maxima, over four and three months respectively, were selected. These were fitted with a Fréchet distribution following the Lieblein (1954) method and extrapolated to give 20 and 50-year return values.

As noted earlier no verification trials were reported.

(c) Some Key Results

The extreme hourly-averaged wind speeds and significant wave heights presented by Berry et al. (1975) and Dames & Moore (1975) are shown in Table 2.5. The wind speeds were derived for the period June to October using measured wind data at the three stations identified earlier and corrected to give equivalent overwater values. The wave heights are extracted from the Dames & Moore (1975) report.

(d) Limitations

The major limitations appear to be the treatment of storm wind data and the lack of verification trials to test the wind and fetch parameterization and resulting

Table 2.5

Extreme wind speed and significant wave height estimates by Dames & Moore (1975).

	Return Period (yrs)	Site[1] (Figure 2.5) 3	7
hourly averaged wind speed[2] (knots)	10	54	54
	20	59	59
	50	65	65
	100	67	67
signficant wave height[3] H_s (m)	10	3.1	5.2
	20	3.7	6.3
	50	4.6	8.0
	100	5.5	9.8

[1] These data are presented for the two sites referenced in the IRC-1974 study so that the results can be compared. This is consistent with the interpretation Berry et al. (1975) and Dames & Moore (1975) placed on these data in as much as there is no reference to a specific site in Mackenzie Bay in the source material.

[2] Source: Berry et al. (1975). Based on Cape Parry data.

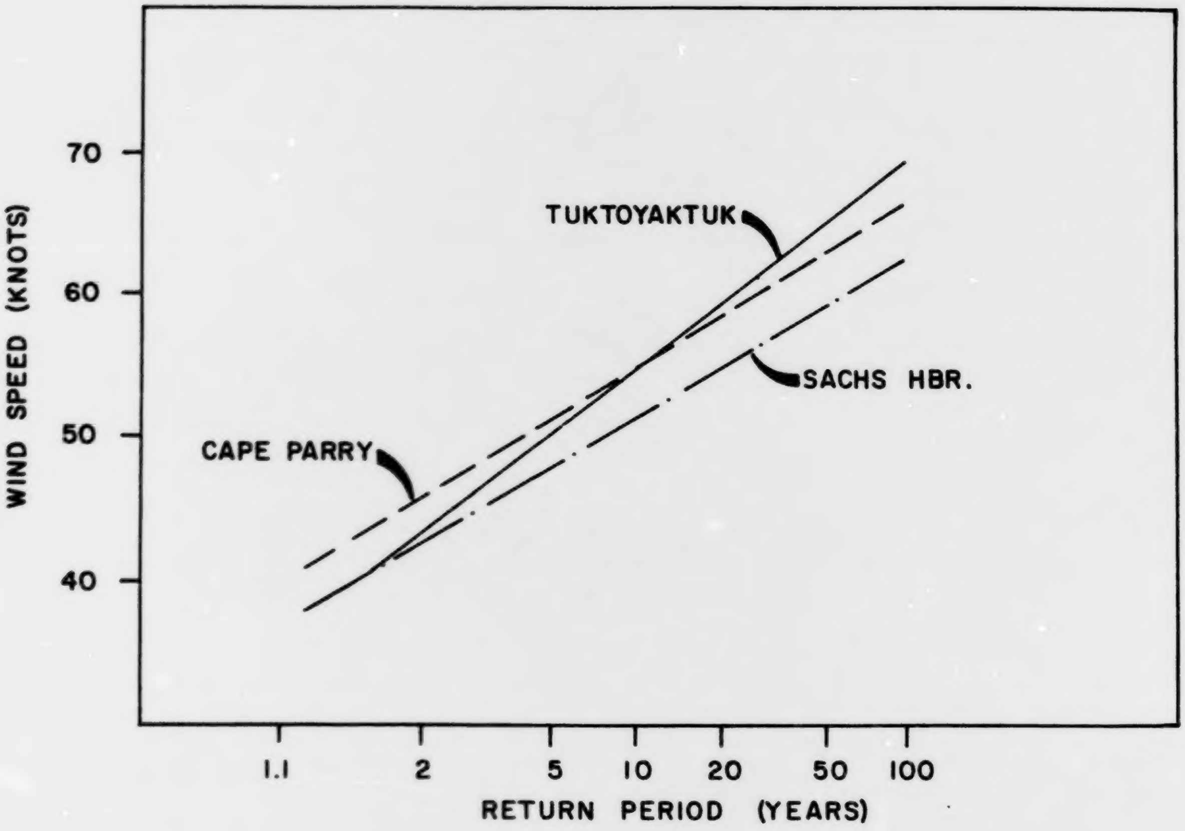
[3] Source: Dames & Moore (1975). The 100-year value was scaled off of the Fréchet distribution graphed in the Dames & Moore report; they were reluctant to include this value in their tables because of the uncertainty attached to it by being so far beyond twice the length of the 19-year data base.

wave heights. The 184 storm results presented by Dames & Moore (1975) show that winds at Tuktoyaktuk were used on only four occasions; otherwise winds at Sachs Harbour and Cape Parry were used to derive the mean wind and duration values for each storm. Combined with the uncertainty in the way in which fetches were determined, i.e. for Franklin Bay or for Mackenzie Bay or for both, these findings lead one to wonder how representative the extreme values really are for Mackenzie Bay. As shown in Figure 2.7, Sachs Harbour and Cape Parry are about 425 km east of Mackenzie Bay and it is not clear how representative winds measured at these stations would be for Class 1 and 2 storms (NW to N winds) generating waves in Mackenzie Bay. We note that the distributions of wind speed maxima, derived by Berry et al. (1975) for the three sites (Figure 2.9) imply some spatial variation. Further comment on the choice of storms and the maximum winds and wave heights in each year is included in Section 2.7.

2.4 Brower - 1977

In 1977 extreme wind and wave values were published by NOAA in the Climatic Atlas of the Outer Continental Shelf Waters and Coastal Regions of Alaska, for the Chukchi and Beaufort Seas. These data were compiled and edited by Brower et al. (1977).

The general approach followed by Brower and his co-workers was to establish extreme wind distributions for coastal stations along the Alaskan North Slope and then scale these distributions to give a wave height distribution from which the extreme values were in turn derived. As will be seen shortly the results are some of the most surprising in the literature, with very interesting implications about the independence of wave heights from ice cover!



Note: Berry et al. (1975) presented these distributions without showing the measured wind maxima, not the author!

Figure 2.9 Distribution curves for maximum measured winds at three stations. (Source: Berry et al., 1975).

(a) Data Sources

Measured wind speed and direction data at Point Barrow and Barter Island (Figure 2.10) between 1949 and 1975 were used to derive the monthly mean winds (which are needed in the wave height calculation) and the extreme value estimates of one-minute averaged wind speed. There is no indication in the climatic atlas of any attempt to verify the wave height distribution with measurements, but this is, perhaps, understandable given the paucity of data for this purpose.

(b) Methods

Annual maximum sustained (one-minute) wind speeds for the coastal station measurements at Point Barrow and Barter Island were extracted from the 26 years of data, apparently without regard to direction or season. These values were then fitted to a Fréchet (Fisher-Tippett Type II) distribution and extrapolated for long return period wind speeds. No directional information is provided. Confidence levels (68 percent) were obtained using procedures described by Lieblein (1954).

To estimate the wave heights Brower et al. (1977) reference the work of Thom (1973a, 1973b), a brief summary of which follows. The basic idea is this. From monthly mean wind data extending over several years one can select the maximum value out of the 12 annual means $\overline{V}_{max}$ to define a scale parameter $b_{\overline{V}}$ for a Fréchet distribution of extreme wind speeds, i.e.

$$b_{\overline{V}} = \sqrt{(373.8 \ \overline{V}_{max} + 542.4)} - 23.3 \qquad (2.5)$$

with units of mph. The shape parameter is given by

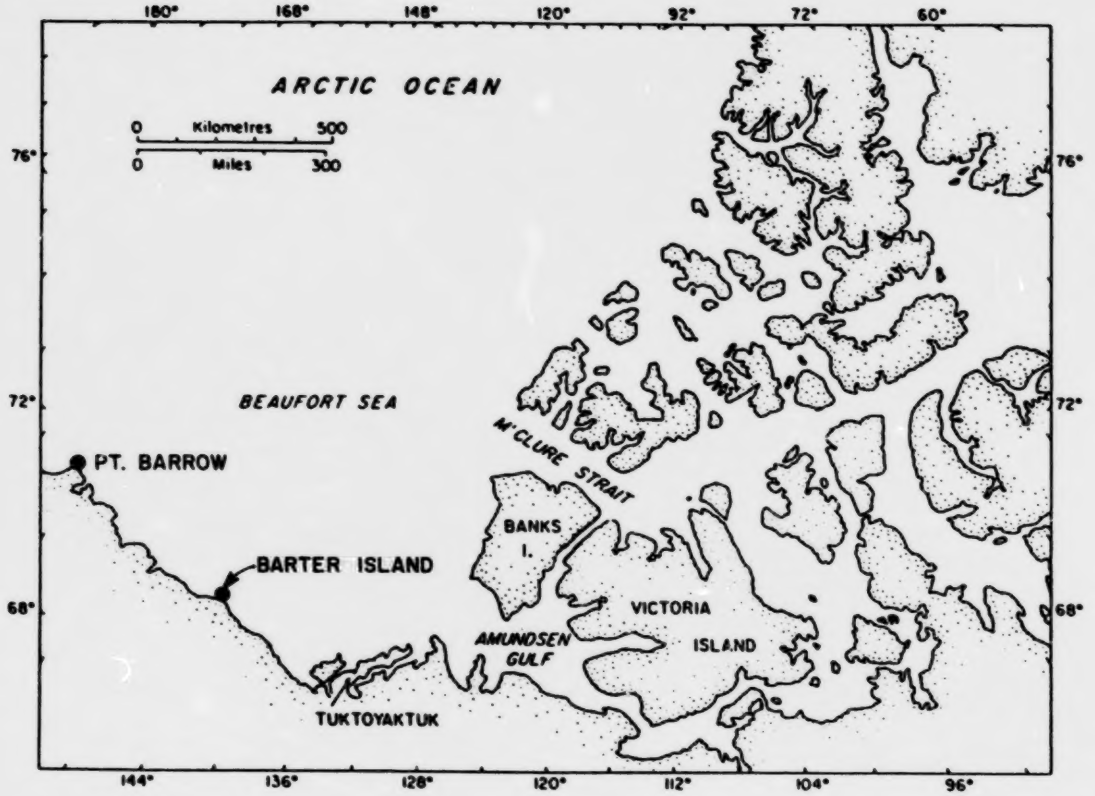


Figure 2.10 Locations of measured winds used by Brower - 1977.

$g_{\overline{V}} = 9.0$ (Thom, 1973a). Thom (1973b) then argues that the scale and shape parameters b_s, g_s for an analogous significant wave height distribution can be found by simply scaling $b_{\overline{V}}$ and $g_{\overline{V}}$. The relations are

$$b_s = 0.455\, b_{\overline{V}} \qquad (2.6)$$
$$g_s = \frac{2}{3}\, g_{\overline{V}} = 6.0$$

from which the wave height distribution can be written

$$P(H_s) = \exp\left(-\left(\frac{H_s}{b_s}\right)^{-g_s}\right) \qquad (2.7)$$

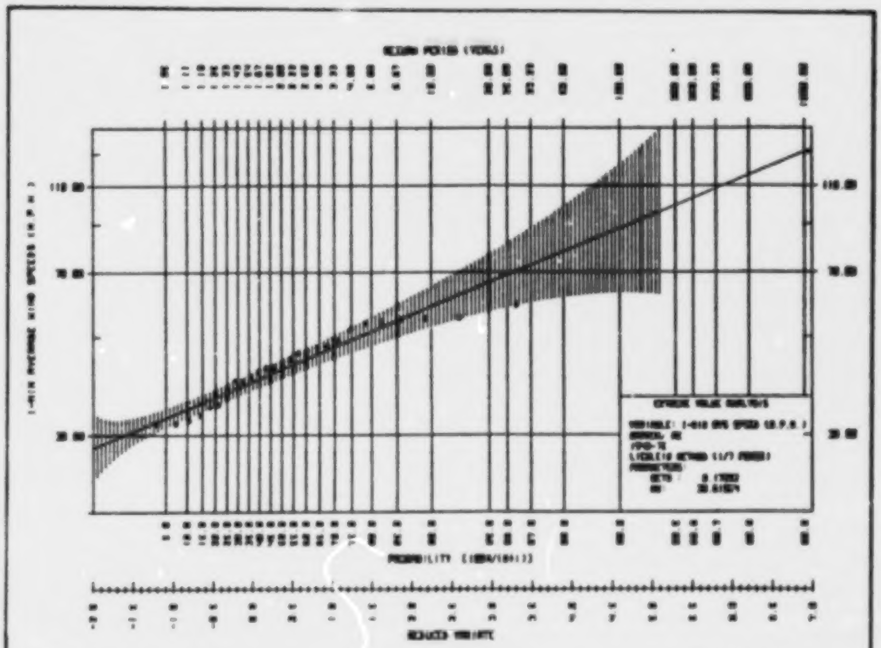
Inverting this expression gives

$$H_s(P) = \exp\left(\ell n\, b_s - \frac{\ell n(\ell n \frac{1}{P})}{g_s}\right) \qquad (2.8)$$

for the significant wave which will be exceeded only once in $(1-P)^{-1}$ years. Note that H_s is in feet in these expressions since the scale factor, 0.455, in (2.6) must have units of feet/mph. Thom (1973b) justifies these parameter conversions by comparison with fitted data from offshore weather ships, fits which seem quite reasonable in his publications. The wave height result depends, then, on the value of $\overline{V}_{max}$ which is calculated from data. Thus one can go simply from an annual maximum monthly mean wind speed to a significant wave height with a specified return period. Brower et al. (1977) infer that this is the approach they followed.

(c) Results

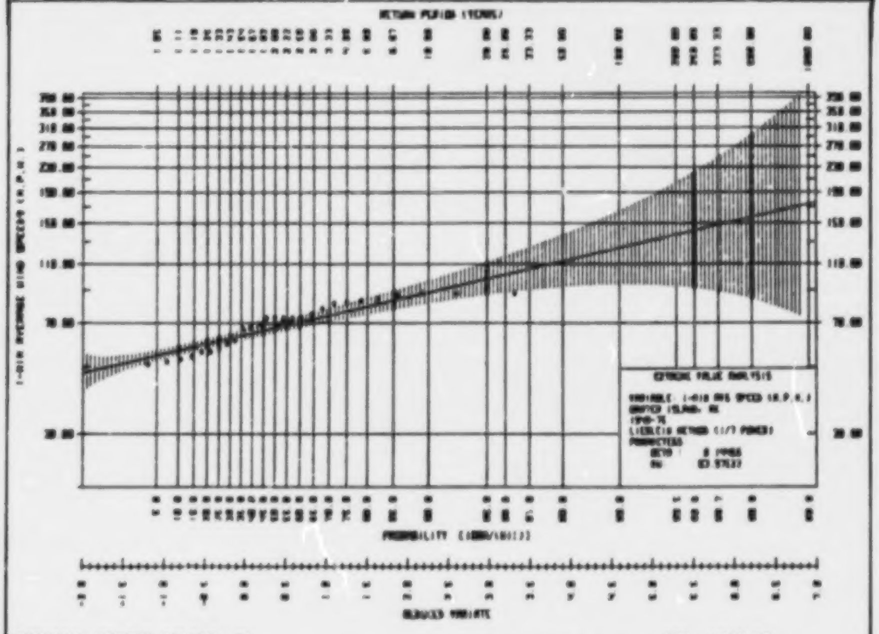
The extreme value extrapolations for sustained wind speed at Point Barrow and Barter Island are shown in Figure 2.11 with the legend given in Table 2.6. The extreme wave heights (significant and $\mu(H_{max}$-3 hr) defined as 1.8 H_s) are shown in Table 2.7. These values



STATION: BARROW, AK POR: 1949-73

RETURN PERIOD—YEARS

	2	5	10	25	50	100	200	1000
UPPER BOUND (MPH)	44.29	53.33	64.96	81.36	98.43	122.43	158.69	374.69
WIND ESTIMATE (MPH)	42.21	51.35	58.47	68.88	77.79	87.78	99.04	130.01
LOWER BOUND (MPH)	40.23	47.66	52.62	58.32	61.48	62.93	61.83	45.67



STATION: BARTER ISLAND, AK POR: 1949-73

RETURN PERIOD—YEARS

	2	5	10	25	50	100	200	1000
UPPER BOUND (MPH)	70.22	84.39	96.75	116.79	136.98	164.41	204.04	419.09
WIND ESTIMATE (MPH)	67.46	79.48	88.59	101.62	112.50	124.46	137.63	173.77
LOWER BOUND (MPH)	64.99	74.67	81.12	88.41	92.46	94.21	92.84	72.05

Figure 2.11 Extreme wind speed distributions presented by Brower - 1977.

Table 2.6

Legend for Figure 2.11
(Source: Brower et al., 1977).

Legend

Annual maximum sustained winds for selected return periods

Values of annual maximum sustained wind speeds for selected return periods in years are presented in graphic and tabular form for selected coastal stations. For example, on the average Barrow can expect annual maximum sustained wind speed to exceed 88 mph once in 100 years. Stated another way, the probability is 0.99 that the maximum sustained wind will be equal to or less than 88 mph; the probability of exceeding 88 mph in any year is 0.01 (the return period is the reciprocal of the latter probability). This is an estimate of the true 100-year return period value; the probability is 0.68 that the true 100-year value lies in the interval bounded by 63 and 122 mph.

Table 2.7

Extreme value estimates for wind speed and wave height by Brower - 1977.

Legend

Annual maximum winds and waves for selected return periods—Marine areas

Return periods for maximum sustained winds and for maximum significant and extreme wave heights are presented in tabular form for selected marine areas. Sustained winds are winds averaged over a period of one minute, the significant wave height is the average height of the highest one third of all waves (sea and swell) in view, and the extreme wave height is an empirical estimate of 1.8 times the significant wave height. Estimates presented in the tables were based primarily on methods described by Thom (see References). For example, on the average the Marine Area A can expect annual maximum sustained wind speed to exceed 97 knots once in 100 years.

Area B

Return period years	Maximum sustained wind-knots	Maximum significant wave-meters (feet)	Extreme wave-meters (feet)
5	57	10.0 (33)	18.0 (59)
10	62	11.3 (37)	20.5 (67)
25	69	13.0 (43)	24.0 (78)
50	75	15.0 (49)	27.0 (88)
100	81	17.0 (55)	30.0 (99)

are given for the entire Beaufort Sea without reference to any specific site. This likely follows from having only two wind stations and the use of Thom's methods. The wave heights would apply to a region bounded on the east by Mackenzie Bay and by continental Alaska on the west.

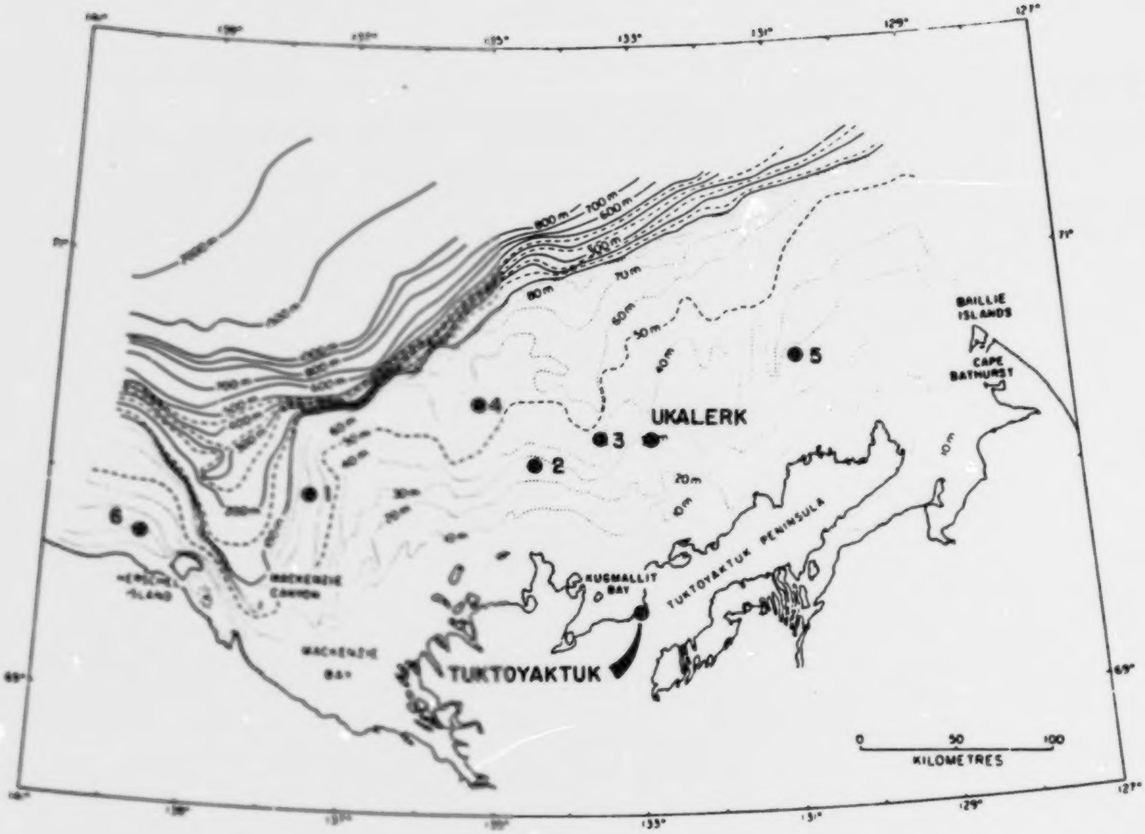
(d) Limitations

The major limitation on these results is that they do not reflect the probability of ice-restricted fetch on the occurrence of extreme wave heights. From Thom's work the wave height Fréchet distribution was fitted and verified with data collected at weather ships operating in the mid-Atlantic and Pacific Oceans. Waves were likely limited by storm wind duration in most cases, a situation which would obtain much more rarely in the Beaufort Sea. Thus it seems unlikely that the scaling relations published by Thom (1973a, b) would apply in this area without modification.

It is also not clear if the maximum wind $\overline{V}_{max}$ was chosen from a particular season, say July to October corresponding with open water, or from the 12-month data set. If the latter is true then there is a possibility that $\overline{V}_{max}$ was biased high by winter storms and consequently $H_s(P)$ also.

2.5 Hydrotechnology - 1980

In 1980 Gulf Canada Resources Inc. commissioned a hindcast of normal and extreme wave conditions at the six sites shown in Figure 2.12. This study was reported by Hydrotechnology Ltd. in December, 1980 and followed a well established approach to deriving the extreme wave height and period required for 20 and 50-year return



Site No.	Position	Name
1	69°57'N 136°30'W	- Tarsuit
2	70°5'30"N 134°27'W	- North Issungnak
3	70°14'N 133°30'W	- West Tingmiark
4	70°24'N 135°12'W	- Kopanoar
5	70°34'N 130°50'W	- Kaglulik
6	69°45'N 139°45'W	- Natsek

Figure 2.12 Hindcast sites for the Hydrotechnology - 1980 study.

periods (Baird and Hall, 1980). Ten years (1970 to 1979) of wind data at Tuktoyaktuk were scaled to give overwater winds, and these were used in a parametric wave model developed initially at Public Works, Canada (Baird, 1978) to hindcast time series of wave heights and periods for each site. Straight-line fetches were used for input to the model defined by a one-tenth ice edge position. The annual maximum wave heigths were then extrapolated using Gumbel's technique (Gumbel, 1954) to give the 20 and 50-year return period extremes.

(a) Data Sources

In this study considerable effort was directed at verifying ratios between overland and overwater wind speeds. Hourly mean wind data for this purpose were obtained at

Tuktoyaktuk	1970 to 1978
Kopanoar	1976 to 1979 (August to October) 74°24'N 135°06'W
Ukalerk	1977 to 1979 (July to October) 70°11'N 132°45'W

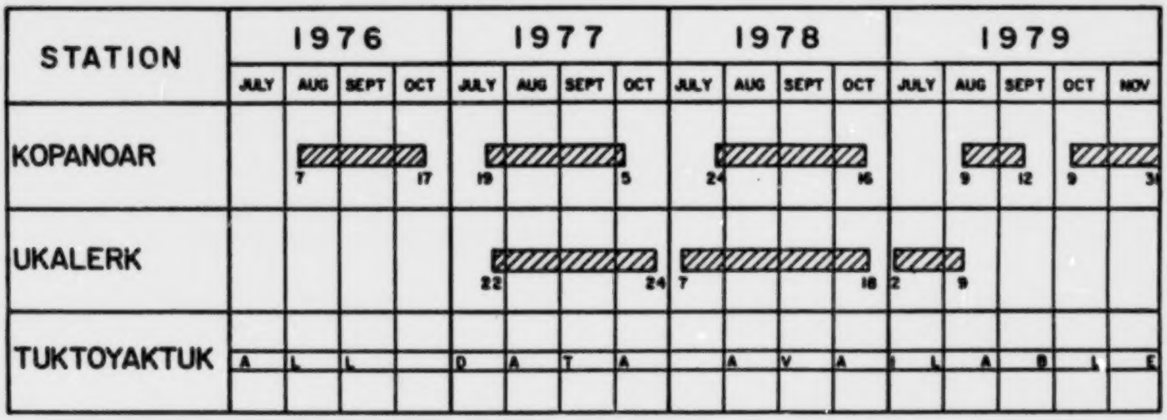
(See Figure 2.12 and Table 2.8.)

Waverider data from 1975 to 1979 were examined and used to verify the hindcast procedures. Disposition of these data, acquired from the Marine Environmental Data Services, is discussed in Chapter 3.

As in the other studies the ice charts prepared by Ice

Table 2.8

AVAILABLE WIND DATA USED FOR THE WIND RATIO ANALYSIS BY HYDROTECHNOLOGY- 1981



Forecast Central, Environment Canada, were used to delineate fetches.

(b) Methods

Following tests of the AES procedures for scaling overland winds to give overwater wind speeds (Richards et al., 1966; Berry et al., 1975), Hydrotechnology developed a new set of ratios based on the relative frequency of wind speeds in 4 km/hr classes at the three sites mentioned above. These are compared with the AES ratios in Figure 2.13 and the marginal wind speed distributions for the three sites are shown in Figure 2.14. It would appear from the Hydrotechnology report that these distributions are the basis for deriving the ratios and are not to be regarded as verification that the ratios are necessarily accurate outside of the data from which they were derived.

The wave hindcasting procedure used by Hydrotechnology was initially developed by Public Works Canada (Baird, 1978) and is based on the dimensionless relationship between significant wave height, peak period, fetch and duration presented by Bretschneider (1973) and U.S. Army (1977). This model is improved over the standard SMB hindcast method by accounting for changes in wind direction during storms; in the Hydrotechnology hindcast eight directional sectors were used. Thus major wind events are modelled as time histories rather than by one mean wind and direction.

The ten years of Tuktoyaktuk wind data were scaled to represent overwater conditions and assembled into hourly time series for each open water season (July to October). The speed and direction data, together with fetch in each sector, formed the input to the model. Baird

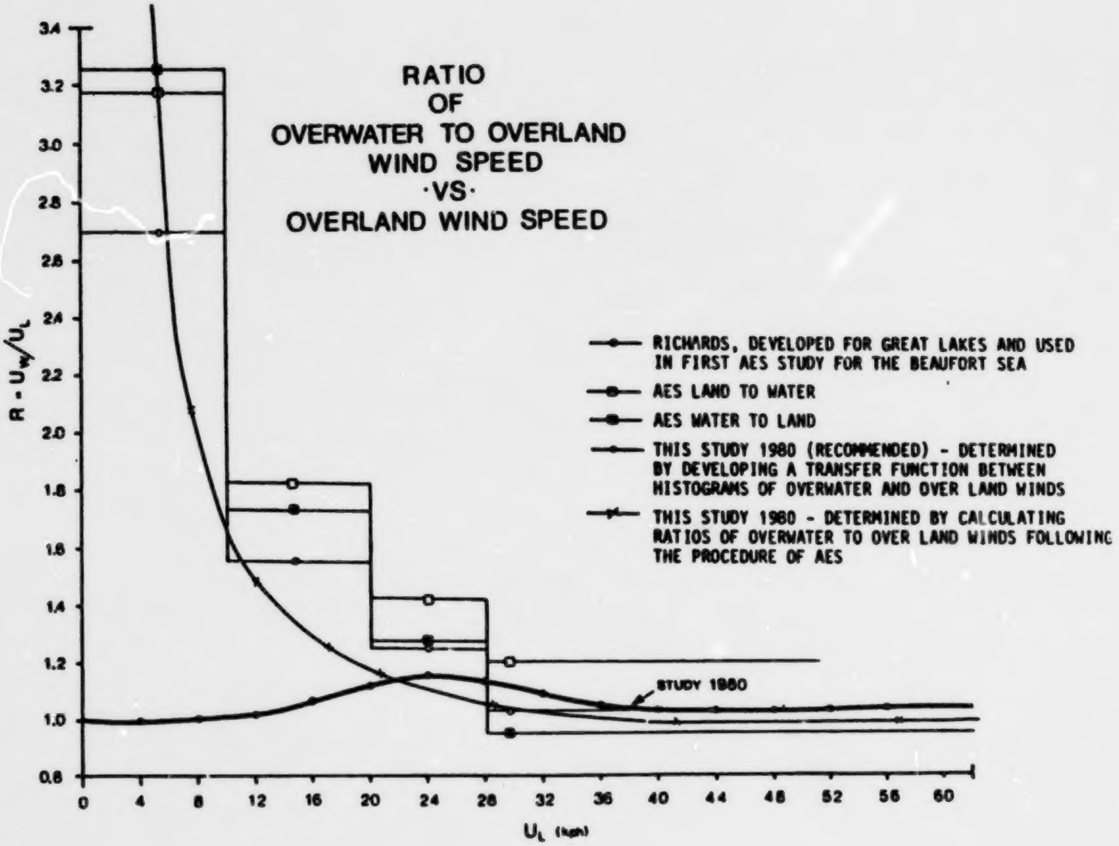


Figure 2.13 Ratios of overwater to overland wind speed from various sources. (Taken from Baird and Hall, 1980).

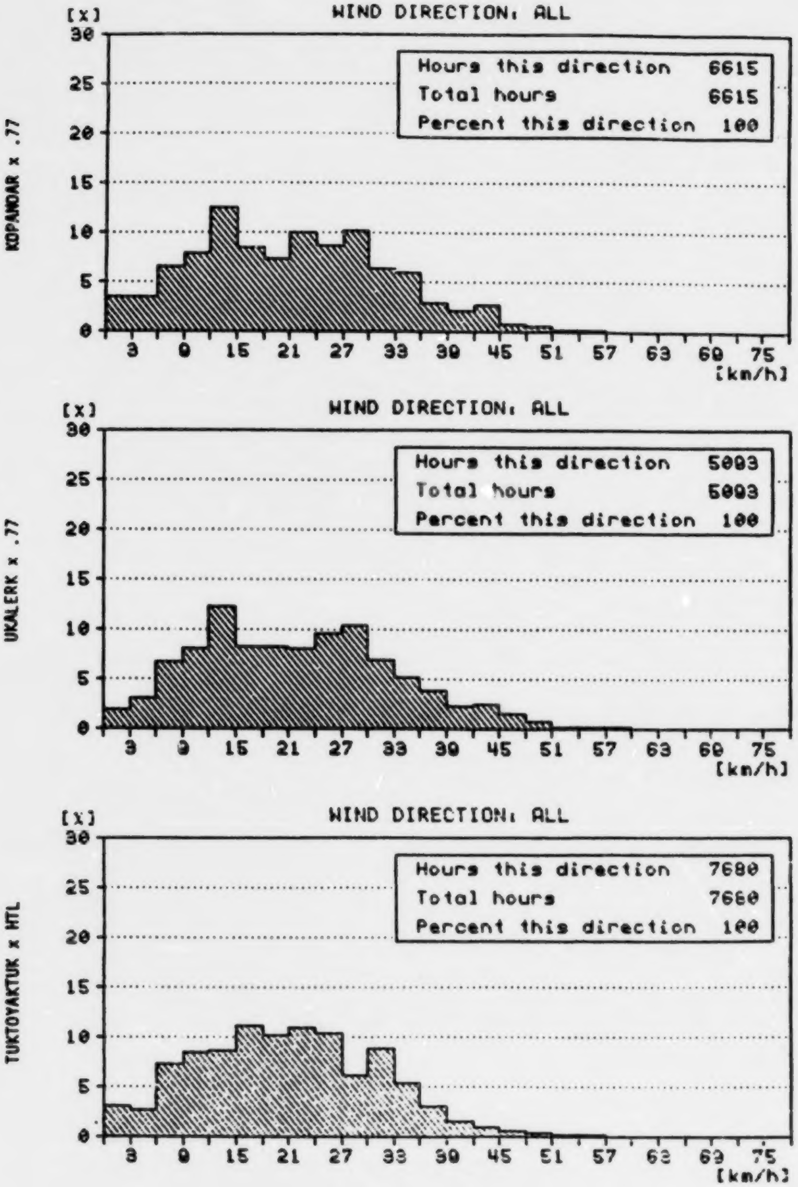


Figure 2.14 Marginal distributions for wind speed at three sites in the Beaufort Sea. (Source: Baird and Hall, 1980).

and Hall (1980) note that the wind direction was smoothed using a 9-point running average. The selection of the 9-point running average was arbitrary and designed only to eliminate rapid changes in wind direction from one directional sector to another.

Using a one hour time step in the model the calculation proceeded as follows. On the first hour of a series of wind values in any one directional sector the recorded value of wind speed with a duration of one hour was hindcasted and the resulting wave height and period were noted. For the second hour, the average speed over the previous hour as well as over the previous two hours were calculated with corresponding durations of one and two hours. The maximum value of wave height and wave period resulting from the two combinations of average speed and duration were recorded.

Extending this procedure, then at any one hour in the sequence of wind data, the average wind speed over the previous n hours was calculated. The associated duration was taken to be n hours and the corresponding wave height and period were hindcasted. The calculations were repeated for n = 1, 2,...96 hours or until the wind direction changed. The maximum value of all the wave height parameters resulting from these estimates for the hour being considered was then recorded along with the associated wave period and the wind direction to represent that hour. The program then stepped forward one hour and the process was repeated to give a time series in that sector.

When a change in wind direction occurred, the wave height and period, obtained for the hour prior to the change in direction were allowed to decay following a procedure discussed below. For the following hours, provided that the direction did not change again, the averaging procedure described above was used in the new sector. The resulting actively generated waves were then added, for that hour, to the decaying waves by taking the square root of the sum of the squares of the actively generated wave height parameter and all decaying wave height parameters. The wave period and direction recorded were that of the largest wave height computed at that hour.

The wave height decay was taken to be proportional to (1-t/T) where the parameter t is the time after the decay started and T is a constant equal to the fetch length divided by the deep water wave group velocity, which was calculated from the initial value of the wave period. The fetch length used was the minimum value of the coded fetch length or the duration-limited fetch (it is only equal to the coded fetch length when the wave generated is fetch-limited). The attenuation of wave period was similarly taken to be proportional to (1-t/T).

Fetch lengths were defined using straight line estimates representative of the distance from the hindcast location to the topographic or ice limits within the sector being considered. The ice limits used by Baird and Hall (1980) were considered constant for each month and were defined by the average location of the one-tenth ice cover for that month.

From the time series of H_s for each season in the 10 year database the maximum height was selected. Data from 1974 were excluded because for all practical purposes Baird and Hall (1980) concluded that the Beaufort Sea was ice-bound. The nine seasonal maxima were then fitted with a Fisher-Tippett I distribution (Gumbel's method) and extrapolated to give 2, 5, 10, 15 and 20-year return period estimates. Baird and Hall do not extend their data past 20 years.

(c) Verification

One of the most important aspects of the Hydrotechnology study was the degree to which the wave hindcast procedures were verified. Two approaches were taken. Firstly, time series of H_s and T_s predicted by the model were superimposed on time series of Hm_o and T_p measured by the Waverider buoys for visual comparison. The hindcast data were assessed for their overall reproduction of the measured series, although an analysis of the model performance for the major storms, i.e. percentage error in the maximum wave heights and whether or not a bias in heights was present between model and observed, was not discussed by Baird and Hall (1980). Secondly, the frequencies of occurrence of H_s and T_s were compared with those of the wave data measured at Kopanoar. This type of comparison is relevant for assessing the model performance for wave climatological purposes (which was part of the Hydrotechnology study) but is not particularly meaningful for extreme value analysis.

Examples of the time series comparisons are shown in Figure 2.15 for August/September 1977, when according to Baird and Hall (1980) "generally good comparison between recorded and hindcast data exists for...1977...with the exception of some storms, most notably the storm of August 26-30, 1977." The authors note that comparisons in 1979 (Figure 2.16) were significantly poorer than in the previous three years of data. The exact reasons for this are not known although the overwater wind data are indicated as the likely source of error.

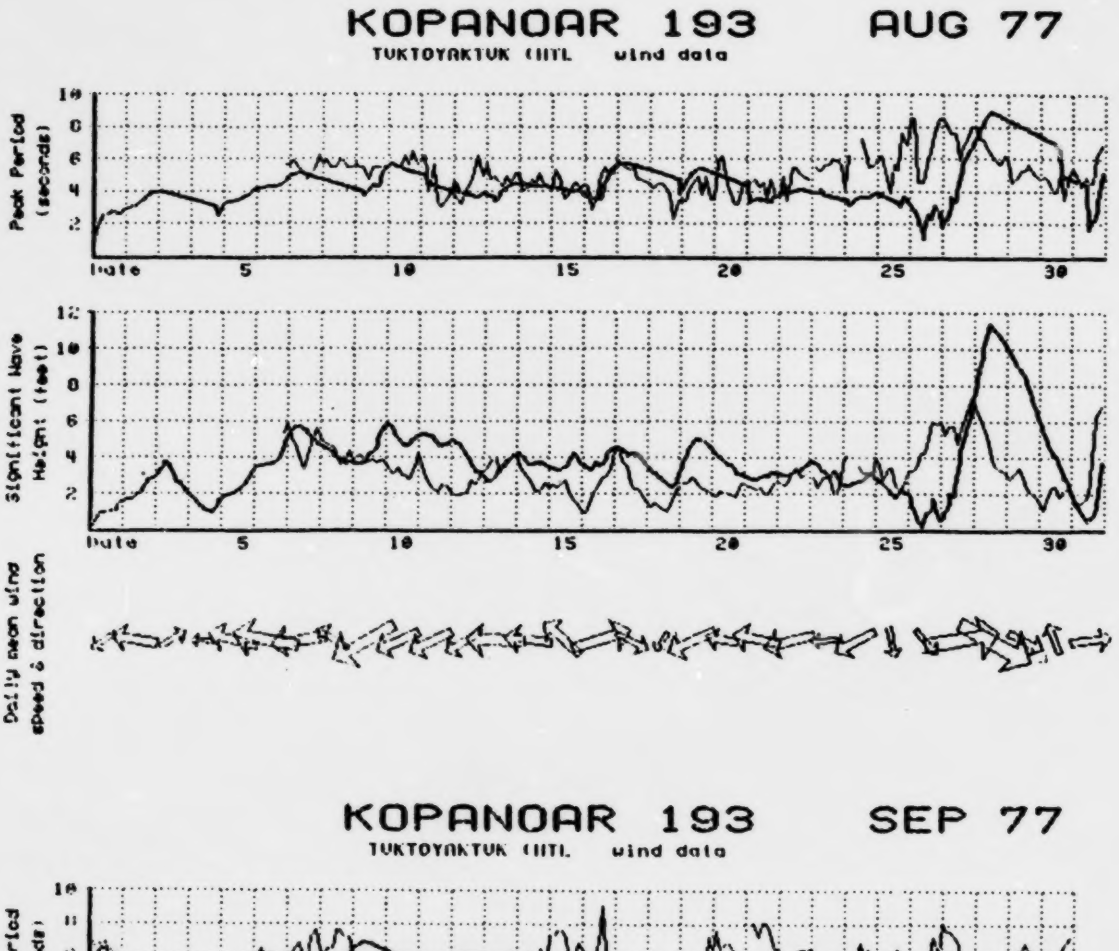


Figure 2.15 Comparison between hindcast and measured wave data, August and September, 1977, Hydrotechnology - 1980 Study (Source: Baird and Hall, 1980).

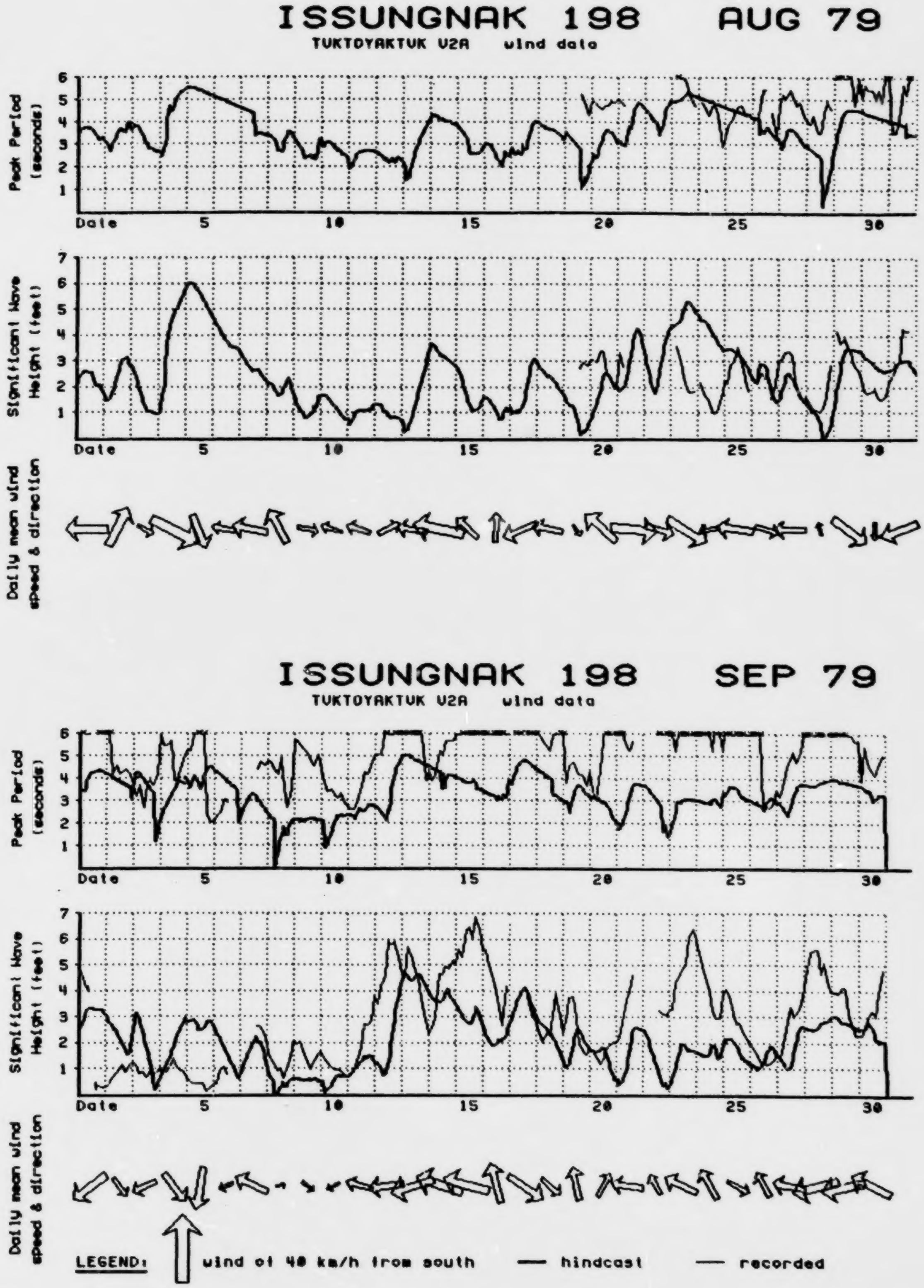


Figure 2.16 Comparison between hindcast and measured wave data, August and September, 1979. Hydrotechnology - 1980 Study (Source: Baird and Hall, 1980).

There are differences in how well the hindcast and measured wave heights and periods agree between different instruments recording the same wind events simultaneously; in fact, the Waverider data show that wave conditions, particularly during storms, are not spatially uniform over Mackenzie Bay. Considering this and the approximations inherent in using a single point-source wind with the Bretschneider equations, Baird and Hall remark that better comparisons than they achieved would be unlikely.

The lack of assessment of the model performance specifically for the larger wave events and the obvious variability in the goodness-of-fit of the two types of wave data limit confidence which can be placed in the extreme values. This is because, for a sample of nine maxima, the FT-I fit is sensitive to the larger wave heights in the set.

The statistical comparisons for significant wave height and peak period are shown in Figure 2.17. The data in 1977 are well modelled; however, about a one-second shift in peak period is noted in the 1978 data. Baird and Hall (1980) were unable to give a reason why the periods in 1978 were consistently underestimated by the model.

(d) Key Results

The extreme wave height estimates at two sites, Kopanoar (4) and Tarsuit (1) (Figure 2.12) have been selected for comparison with other hindcasts in this study. The FT-I distributions are shown in Figure 2.18. The extreme values are presented in Table 2.9; for 10 and 20-year return periods the values are taken from Baird and Hall (1980) whereas the values for 50 and 100 years have been scaled from their graphs.

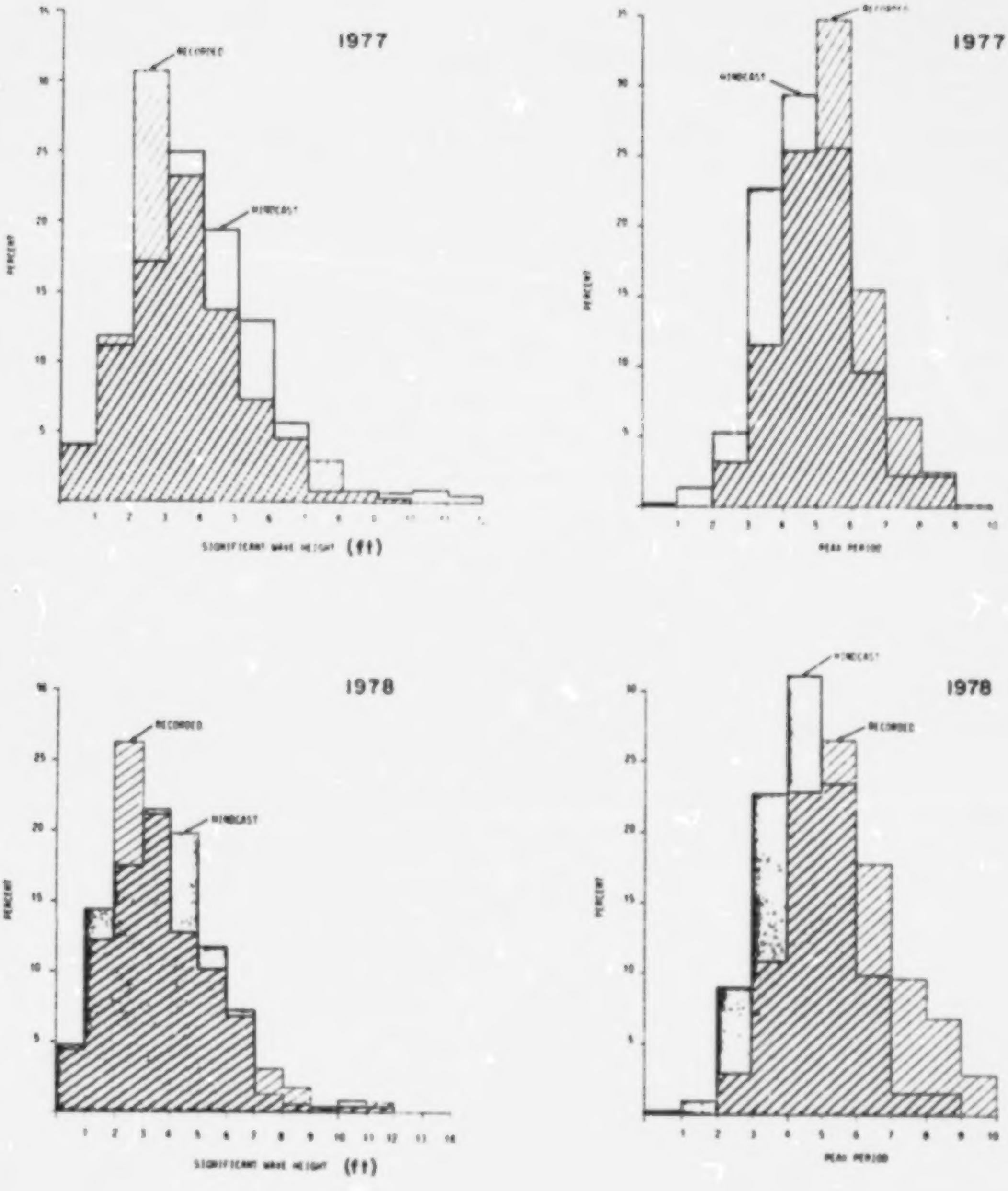


Figure 2.17 Comparison of significant wave height and peak period data at Kopanoar for 1977 and 1978. Hydrotechnology - 1980 study. (Source: Baird and Hall, 1980).

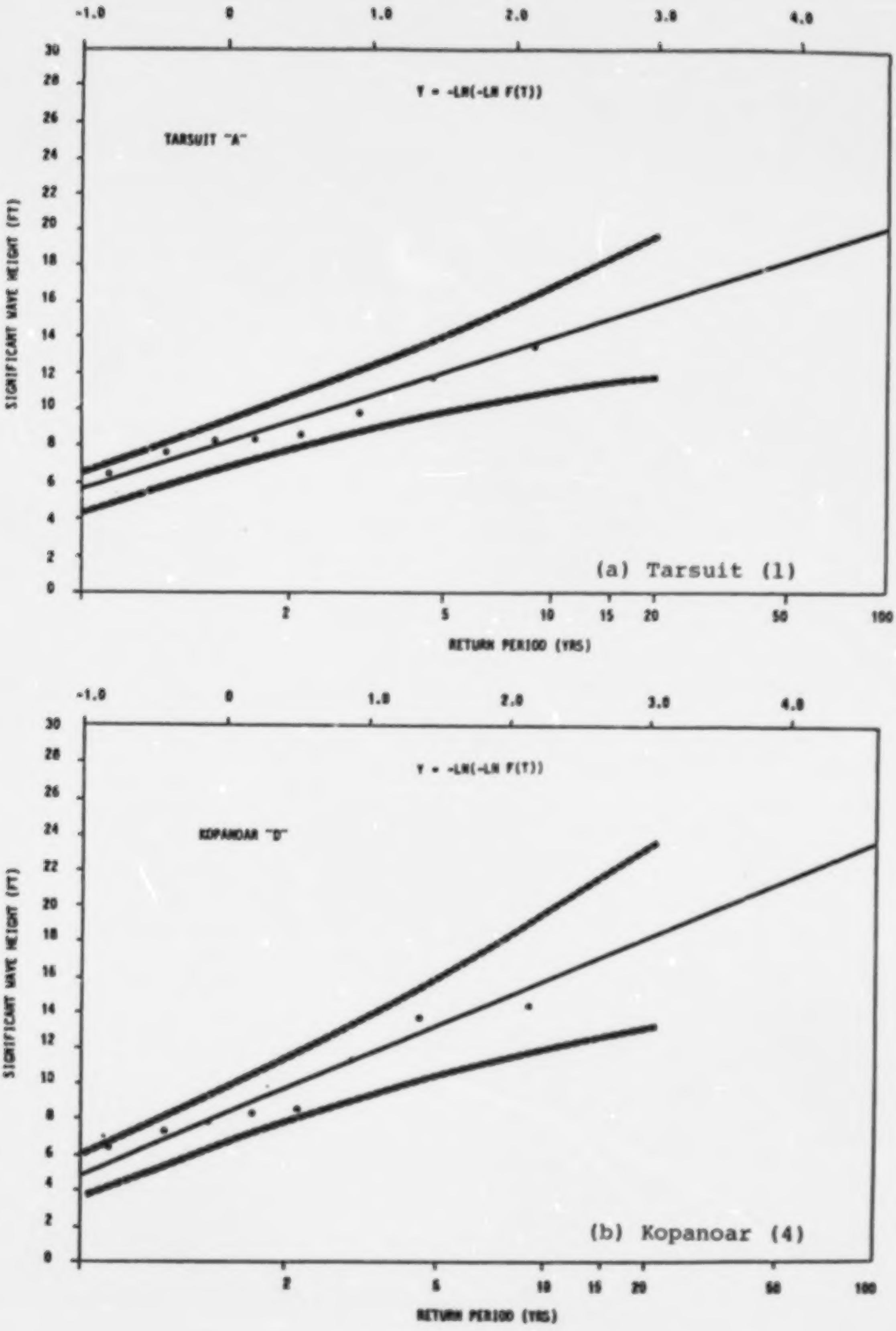


Figure 2.18 Extreme value distributions for significant wave height for Tarsuit (a) and Kopanoar (b) from the Hydrotechnology - 1980 study.

Table 2.9

Extreme wind speed and significant wave height estimates by Hydrotechnology - 1980.

	Return Period (yrs)	Site (Figure 2.12) 1	4
hourly averaged wind speed (knots)	10	44	44
	20	49	49
	50	56	56
	100	59	59
significant wave height H_s (m)	10	4.2	4.8
	20	4.8	5.5
	50	5.7	6.5
	100	6.2	7.3

(c) Limitations

The principal limitations to this study are the lack of verification of overwater winds with data independent from those used to derive the wind transfer function (Figure 2.13), the lack of an assessment of the hindcast model performance for storms in particular, including the influence (if any) on the extreme value distribution, and the limited number of open water seasons (nine) from which to derive the extreme values.

2.6 Seaconsult - 1981

As described earlier in Section 2.2, the IRC hindcast was prepared for Imperial Oil Company, Ltd. in 1974. In succeeding years, 1975, 1976 and 1977 wind and wave data collected in the Beaufort Sea were examined by the Production Department of Imperial Oil and indicated that the IRC hindcast values were too low (Wilson, 1976; Verity, 1977; Anderson, 1978). These observations placed in doubt the extreme values obtained for the 50 and 100-year return periods. Anderson (1978) concluded that an updated hindcast study, taking advantage of the greatly expanded Waverider database (by late 1978) and using more advanced numerical models than the SMB approach were warranted. Consequently Seaconsult Marine Research Ltd., the Danish Hydraulic Institute and the MEP Company were contracted to provide a new hindcast of extreme winds and water levels at the ten sites shown in Figure 2.19.

The approach followed in the Seaconsult hindcast was fundamentally different than previous studies; it can be classed as an extreme storm hindcast inasmuch as the water levels were calculated directly from intensified storms having 50 and 100-year return periods. All

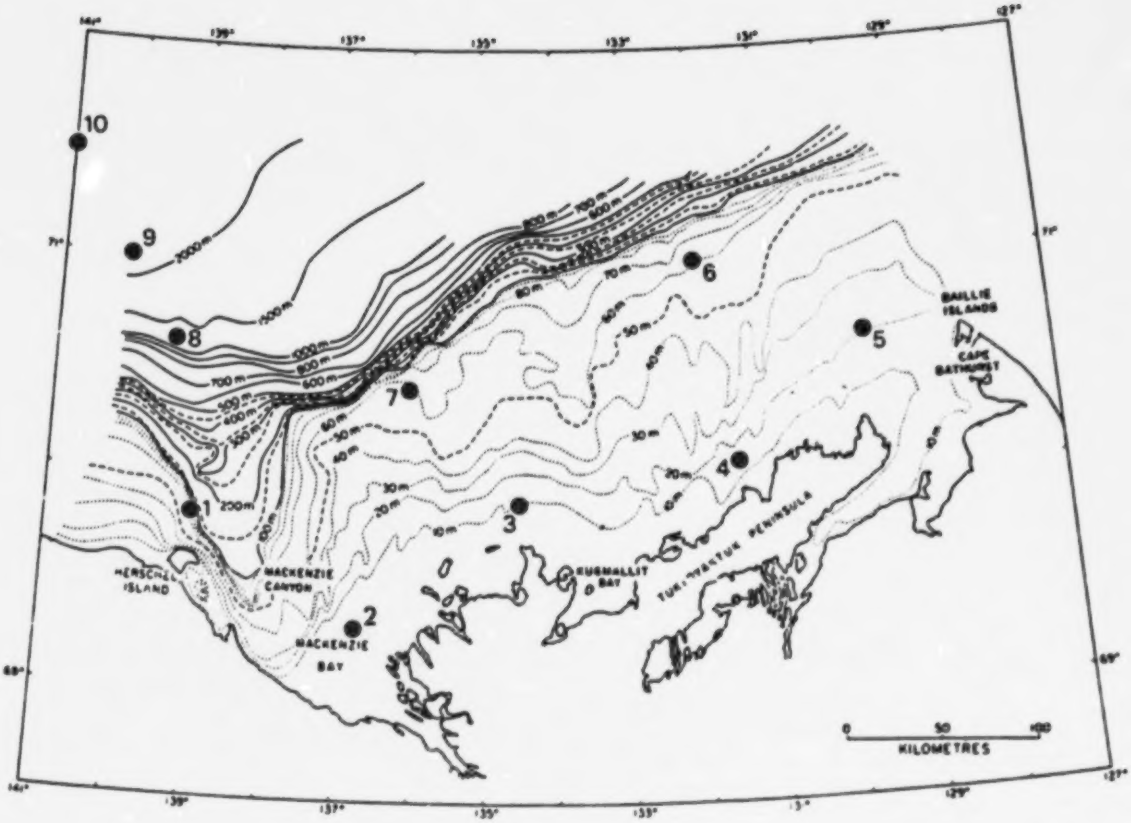


Figure 2.19 The ten ESSO hindcast sites in the Beaufort Sea. (Source: Hodgins et al., 1981).

statistical extrapolation of environmental parameters was confined to the wind data alone. This approach was adopted for a number of reasons:

- directional spectral wave data could be hindcasted, allowing for refraction and shoaling, and providing much more information about the design sea-state conditions than obtained from parametric hindcasts;
- two-dimensional wind fields and open water areas could be mapped fairly accurately, at least to the resolution of the model grid, thereby reducing the uncertainty in wave heights associated with "effective fetch" estimates;
- simultaneous surge and wind-wave conditions produced by the same meteorological event could be evaluated; and
- the reasonableness of the storms producing the extreme sea-states could be examined and discussed.

The principal difficulty with this procedure is, of course, pinning down the return period of the wave conditions. This is because the influence of sea ice is separated and treated independently from that of the storms in deriving each extreme sea-state. In the other studies where a sequence of observed wind and ice conditions was modelled to give wave heights, and these wave heights were then extrapolated to give extreme values, the probabilities of wind and fetch were assumed to be properly accounted for in the extrapolation procedures.

The Seaconsult hindcast was done as follows. Wind fields were derived every 6 hours for the ten sites using the Canadian Meteorological Centre (CMC) 381-km grid point pressure database. Ten years of data were used, 1969 to 1978. The ten annual maximum wind speeds (irrespective of direction) were then fitted to an FT-I distribution and extrapolated for 50 and 100-year return periods.

Major storms producing large wave and surge measurements in this 10-year database were also examined, and a "prototype" storm, occurring on August 26, 1975, was selected for intensification to give the 10, 50 and 100-year return period events. The intensification was carried out until the peak storm winds in each event matched those obtained by extrapolating the ten years of wind data. The storm surge response and directional frequency wave energy spectra in the southern Beaufort Sea were then hindcasted from the time series of storm wind fields. The sea ice cover was specified in each case by the most northerly observed position of the nine-tenths ice edge. Extreme water levels were then calculated by summing the tidal elevation, the surge and the most probable 3-hour crest elevation at each site, at the return period of the intensified storms. The independent probability of ice conditions sufficient to permit the hindcasted wave conditions was not explicitly taken into account in deriving the return period of water levels.

(a) Data Sources

The wind fields were calculated every 6 hours on the 190.5-km grid shown in Figure 2.20 for the years 1969 to 1978. Mean sea level barometric pressure at each grid point was extracted from the CMC (AES) archive of surface pressure data on the 381-km grid and interpolated. The surface winds at 19.5 m were also calculated from the geostrophic winds using atmospheric stability para-

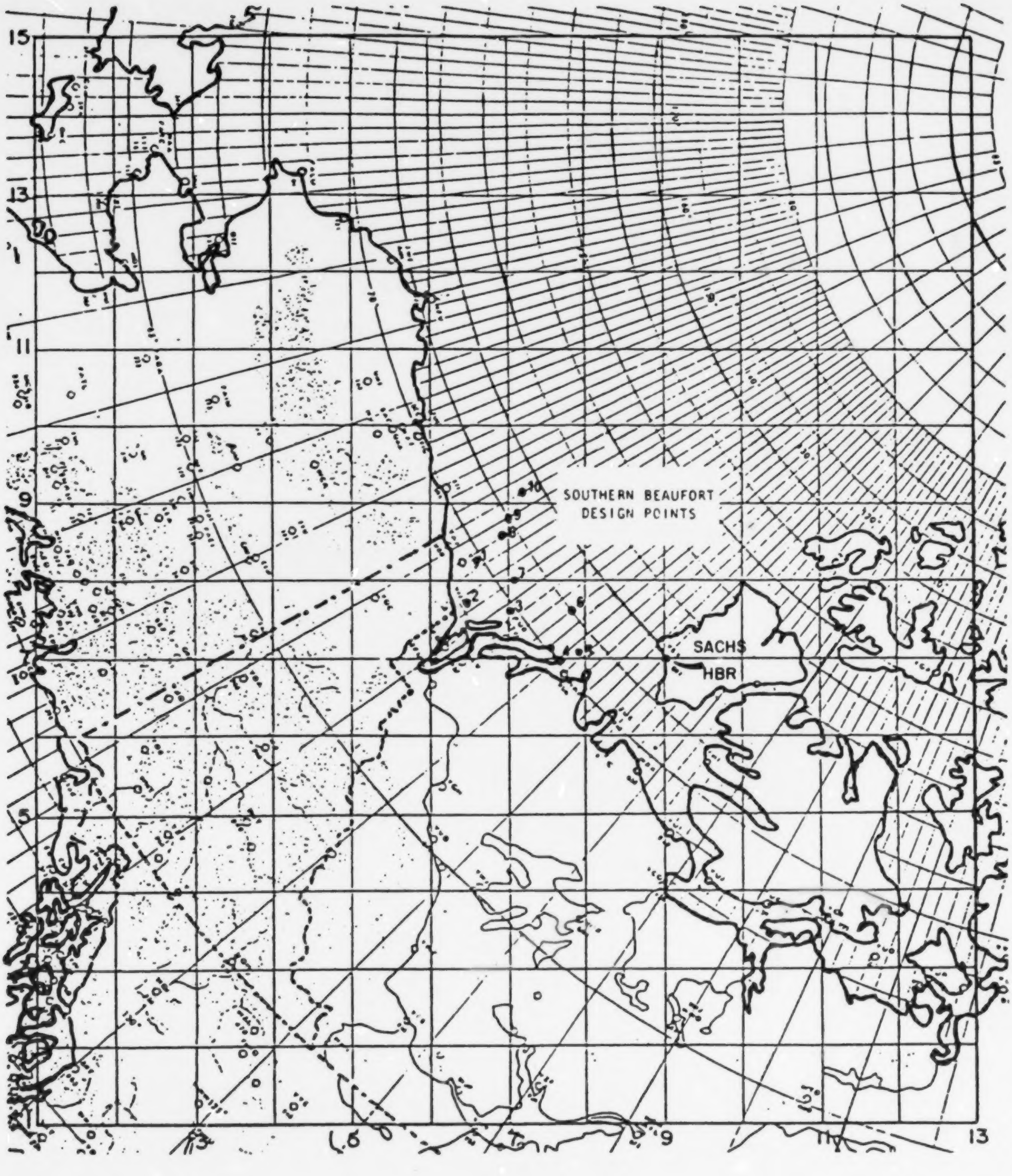


Figure 2.20 The 190.5 km grid used by MEP (1982) to derive the wind fields used in the Seaconsult - 1981 hindcast. This grid is just twice the resolution of the 381 km data grid; pressure data at every second node were used to calculate the geostrophic wind field.

meters derived from radiosonde data at Sachs Harbour. Wind speed and direction measurements at exploratory rig sites and coastal land stations were used to verify the derived wind fields (Table 2.10).

Waverider data (from the Marine Environmental Data Services) collected between 1975 and 1978 were used to verify the wind-wave model (Figure 2.21), although during the course of the hindcast study, it was found that many of the apparently useful Waverider records corresponded to storms too small to be resolved on the 381-km grid. These were discussed in Chapter 1 and tentatively identified as "Arctic instability lows." This greatly limited wave data available for calibration and verification purposes. Consequently the DPW (1971) report of 30-foot wave heights during the storm of September 13-14, 1970 was taken as evidence that waves of about 10 metres height have been observed in the Beaufort Sea. This visual observation is open to interpretation and will be discussed in more detail in Chapter 3.

Water level data were available in 1972, 1975 and 1977 for verification of the storm surge model (Figure 2.21). However, the maximum surges in these years were limited to about 1 m and past inundations of the order of 2.5 to 3.0 m were known to have taken place. Consequently the Seaconsult study made considerable use of indirect water level data--debris lines (Reimnitz and Maurer, 1979) and missionary records--to test the model response to reported winds and surge levels during these events. Records from 1944 and 1970 were examined in detail.

Ice cover boundaries were mapped from the 7-day summary charts prepared for the Beaufort Sea by Ice Branch, AES.

Table 2.10

Disposition of wind measurements used to verify modelled winds in the Seaconsult - 1981 Hindcast (Source: MEP, 1982).

Period	Station Name	Position	Comments
Aug. 31-Sep. 3, 1972	Taglu G-33	69°23'N 134°52'W	12 m anemometer height wind speed only, no direction
Aug. 7-13, 1975	Inmerk NCC-208	69°37'N 135°08'W	
Aug. 23-29, 1975	NCC-208	69°31'N 135°41'W	
Aug. 23-29, 1975	Pullen Is.	69°46'N 134°25'W	
Aug. 23-29, 1975	-	69°44'N 134°54'W	
Aug. 23-29, 1975	-	69°15'N 135°55'W	
Aug. 25-30, 1977	Ukalerk	70°11'N 132°45'W	64 m anemometer height
Aug. 25-30, 1977	Kopanoar	74°24'N 135°06'W	64 m anemometer height
Aug. 25-30, 1977	Nektalorik	70°27'N 136°28'W	30 m anemometer height
	Isserk	69°39'N 134°25'W	

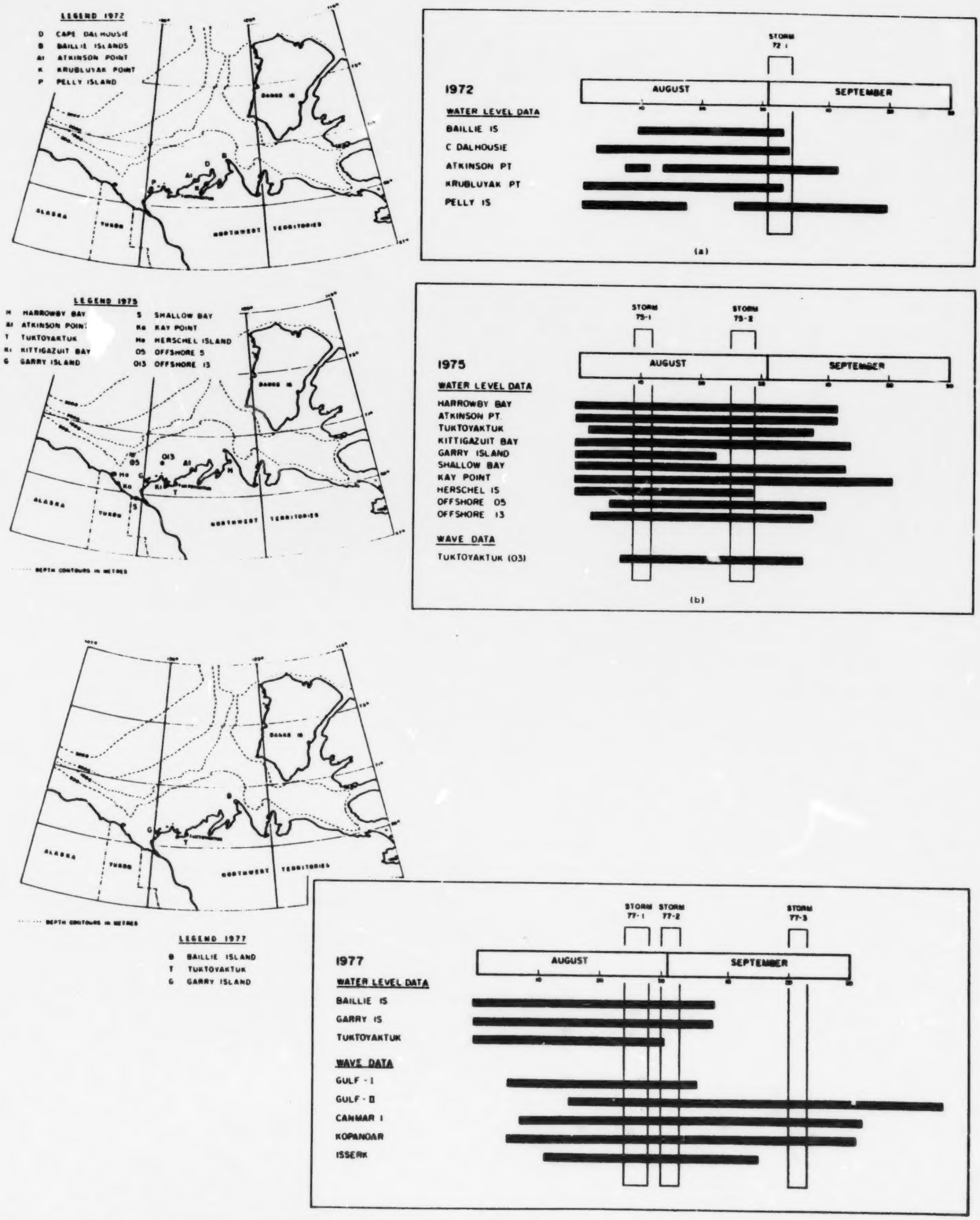


Figure 2.21 Water level and Waverider data used by Seaconsult - 1981.
(Source: Hodgins et al., 1981)

(b) Methods

Wind Fields

Six-hourly geostrophic wind fields were calculated from the 381-km grid point data by fitting orthogonal polynomials to the pressure data following the procedures described by Sykes and Hatton (1976). The pressure gradients, and in turn the wind speeds and directions, were calculated from the polynomial slopes on the 190.5-km working grid (Figure 2.20). Surface winds were calculated from the geostrophic winds using methods proposed by Agnew and Diehl (1978). This involved three basic steps:

- determining the planetary boundary layer height empirically from wind speed and stability considerations (Hanna, 1969);
- determining the surface friction velocity;
- determining the wind profile (following Businger et al., 1971).

Atmospheric stability was estimated from radiosonde data (Sachs Harbour) and assumed surface temperatures. (We note that Sachs Harbour lies on the warm side of the low pressure centre [winds off the land] when storms producing NW winds are most effective in generating severe wave conditions in Mackenzie Bay. These wave-generating winds are on the cold side of the low [off the ice] and the stability characteristics at Sachs Harbour may not be representative of the NW winds along the Alaskan coast.)

At each of the ten sites the extreme winds were derived by assuming that an FT-I distribution represents the hindcasted annual maxima, and extrapolating the fitted distribution to 50 and 100-year return periods. The "prototype" storm 75-2, occurred on August 26 to 28, 1975 (Figure 2.22) and was characterized by 50 knot (1-minute average) winds and approximately 3 to 3-1/2 m significant wave heights (this number is not known more precisely because the Waverider data right at the storm peak were lost). This storm was intensified by deepening the central low pressure and expanding the zone of influence until the geostrophic wind in Mackenzie Bay matched that produced from the FT-I distribution for each return period. This procedure used the wind and pressure field mappings derived from the CMC pressure data as described above. The speed of the storm over the area was not altered by the intensification procedure. At each step the pressure and wind maps were checked by an experienced meteorologist to ensure that the simulated storm was reasonable (MEP, 1982).

MEP also did an error analysis of the wind modelling procedures. These errors were carried through to an estimate of their effect on the 50 and 100-year extreme winds, and consequently on the intensified storms. Altogether, five intensified storms were synthesized which, along with storm 75-2, were hindcasted for wind, waves and surge (Table 2.11):

- storms 75-2, E1, E2 and E3 were regarded as the most probable 1, 10, 50 and 100-year return period events; and

- storms E4 and E5 along with 75-2, E1 and E2 were interpreted as confidence limits on the most probable events at each return period, derived from the error analysis of the wind modelling procedures.

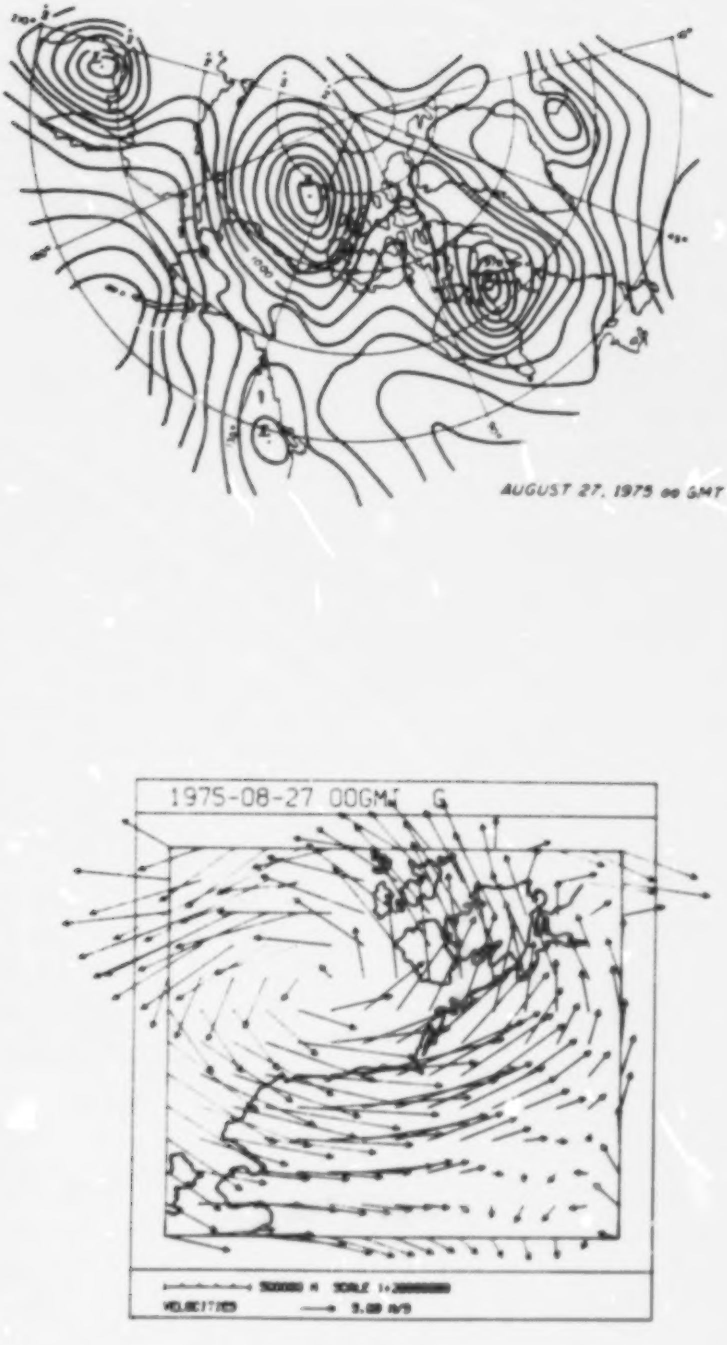


Figure 2.22 The prototype storm used for intensification in the Seaconsult - 1981 hindcast together with the simulated wind field. (Source: Hodgins et al., 1981).

Table 2.11

Correspondence of extreme storms with extreme wind speeds derived from the ten-year data base. (Source: Hodgins et al., 1981).

Return Period (Years)	Extreme Storm Label		Max. Modelled Wind Speed (m/s)	Gumbel Extra-polated Speed(Max) (m/s)
1	E1	UB	25	24
	75-2	MP	20	18
	75-2	LB	20	18
10	E2	UB	30	31
	E1	MP	25	24
	75-2	LB	20	21
50	E4	UB	40	39
	E2	MP	30	31
	E1	LB	25	26
100	E5	UB	45	43
	E3	MP	35	34
	E2	LB	30	29

where UB, MP and LB give the upper bound, most probable and lower bound values respectively.

This arrangement is shown schematically in Figure 2.23 and the time series winds are plotted for a site in central Mackenzie Bay in Figure 2.24 for each storm.

Wave Hindcast Model

The model used by Seaconsult (1981) was a discrete spectral wave energy model developed by the Danish Hydraulic Institute, called the System 20. The model describes the sea state at any given time in terms of a directional frequency wave energy spectrum; it is based upon the conservation of wave energy over time and space and includes source and sink terms. The basic equation states that a component of the directional frequency spectrum moves at its group velocity, being subjected to an increase and decrease of energy depending on the wind speed and direction. Including the effects of refraction produced by changes in water depth, the spectral energy density E obeys the equation

$$\frac{\partial E}{\partial t} + \frac{\cos\theta}{c}\frac{\partial (Ecc_g)}{\partial x} + \frac{\sin\theta}{c}\frac{\partial (Ecc_g)}{\partial y} + \frac{c_g}{c}\left(\sin\theta \frac{\partial c}{\partial x} - \cos\theta \frac{\partial c}{\partial y}\right)\frac{\partial E}{\partial \theta} = \tag{2.9}$$

$$\begin{cases} (A+BE) \quad (1- \left(\frac{E}{E_\infty}\right)^2 & \text{Following wind, } E<E_\infty \\ -\ \alpha Hm_o^2 f^4 E & \text{No wind. Following wind } E>E_\infty \\ -\ \alpha Hm_o^2 f^4 E - BE & \text{Opposing wind} \end{cases}$$

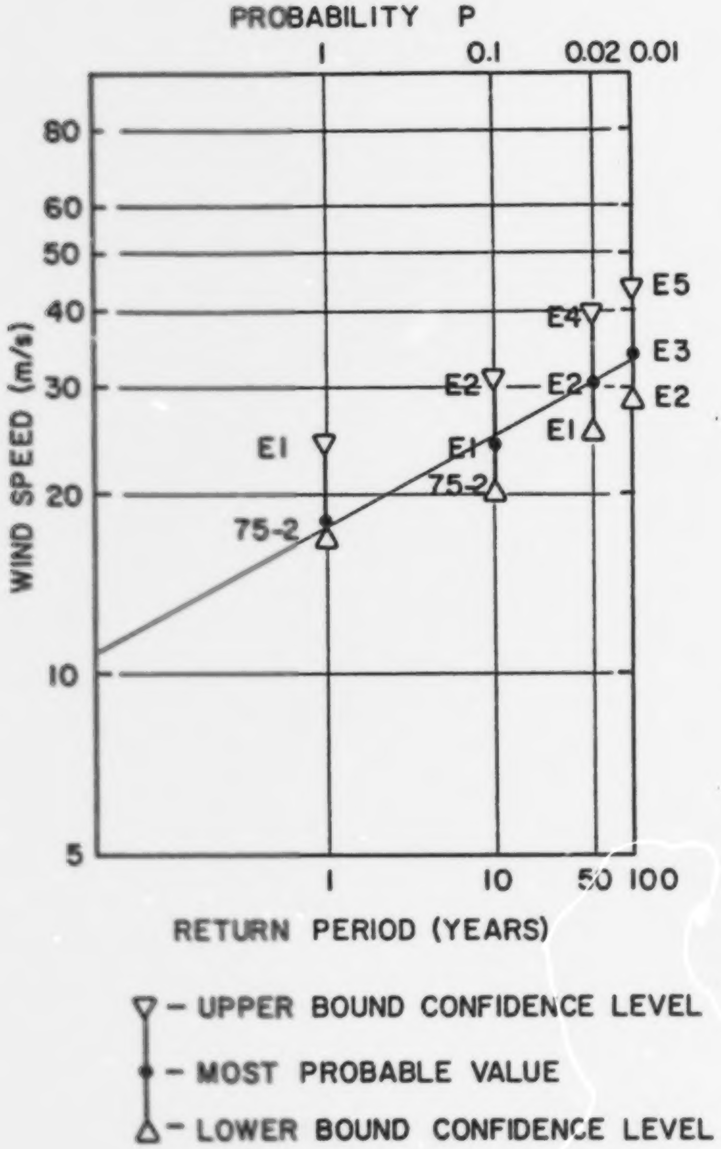


Figure 2.23 Schematic diagram of the relationship between the extrapolated wind speeds and their confidence levels with the extreme storm labels. (Source: Hodgins et al., 1981).

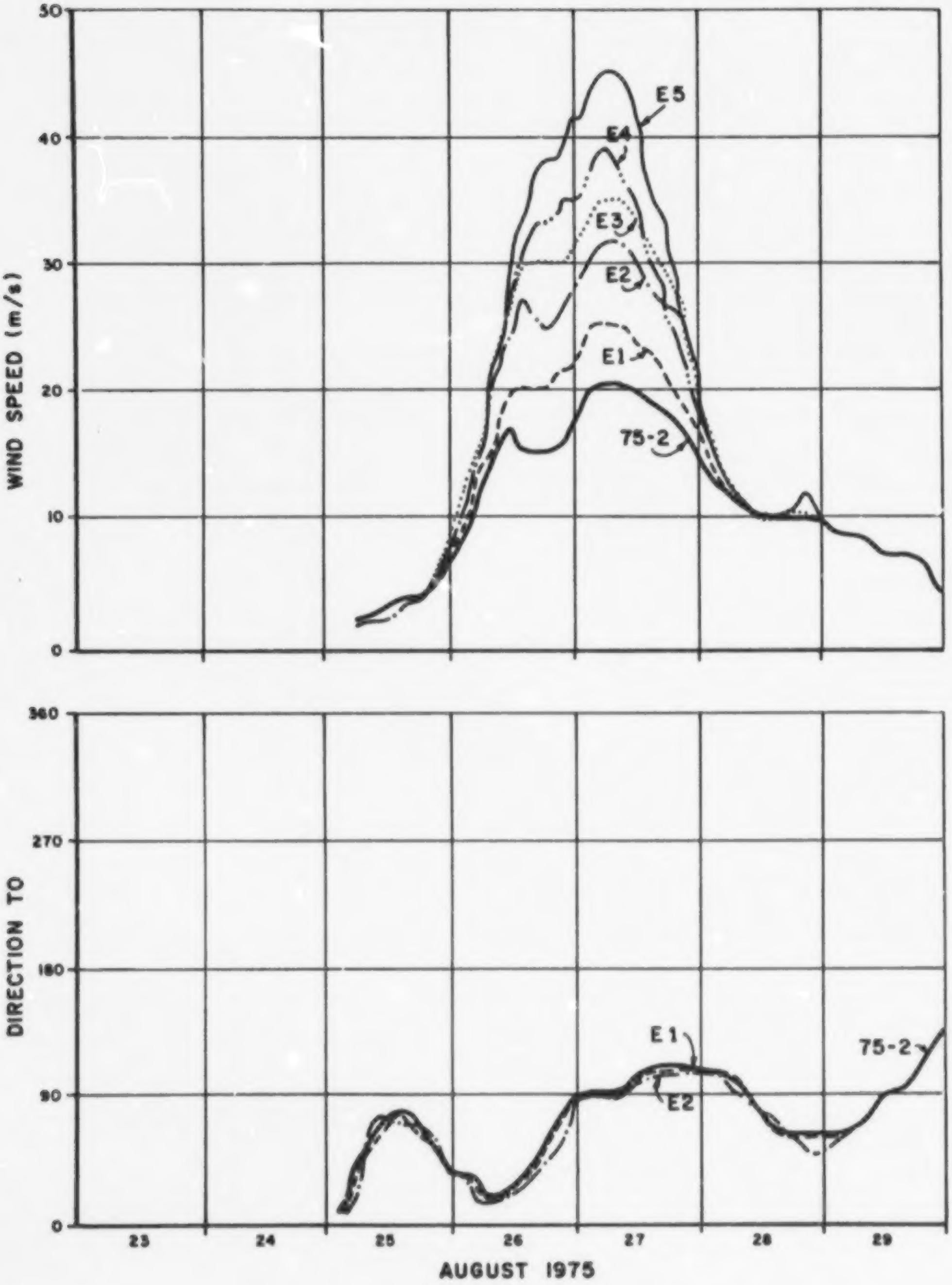


Figure 2.24 Time series of wind speed and direction from the extreme storms. (Source: Hodgins et al., 1981).

where,

$E(x,y,t,f,\theta)$ - directional frequency wave energy spectrum (m^2/Hz)
x,y - orthogonal space coordinates (m)
t - time (s)
f - frequency (Hz)
θ - direction of wave propagation relative to the model grid north
c - phase velocity (m/s)
c_g - group velocity (m/s)
$A(f,\theta,\vec{U})$ - growth term
$B(f,\theta,\vec{U})$ - growth term
$\vec{U}(x,y,t)$ - wind field at 19.5 m (m/s)
$E_\infty(f,\theta,\vec{U})$ - fully developed spectrum
α - damping coefficient ($0.0094\ s^3/m^2$)
Hm_o - significant wave height defined as $4\sqrt{m_o}$, where m_o is the area under the energy spectrum

Equation (2.9) shows that for a given wind velocity the energy spectrum grows to a certain limit, the fully developed spectrum E_∞, at which state the incoming energy from the wind is balanced by the outgoing energy from wave breaking and other dissipation mechanisms. In this model E_∞ was specified by the Pierson-Moskowitz (1964) spectrum. The linear growth term $A(f,\theta,\vec{U})$ takes a form that was proposed by Priestly (1965)

$$A(f,\theta,\vec{U}) = \frac{1.357\cdot10^{-16}\ \omega^3\ U^6\ (\frac{\omega}{U})^{2.23}}{[0.33^2\ (\frac{\omega}{U})^{2.56} + (k_1 - \frac{\omega}{U})^2]\cdot[0.52^2\ (\frac{\omega}{U})^{1.9} + k_2^2]} \qquad (2.10)$$

where,

ω - angular frequency ($2\pi f$)
k_1 - $k|\cos\psi|$
k_2 - $k|\sin\psi|$
k - wave number
ψ - angle between the wind direction and the wave direction

in close agreement with Barnett (1968) and Karlsson (1972). The units of (2.10) are m^2. In the Beaufort Sea hindcast (2.10) was used with $A\ \alpha\ U^6$ for $U \leq 10$ m/s and proportional to 10^2U^4 for U>10 m/s in recognition of too rapid low-frequency growth at high wind speeds (Cardone et al., 1976; Dexter, 1974. The analytical expression for the exponential wave growth term used in this study was demonstrated by Inoue (1967) to fit observations well. The equation is

$$B(f,\vec{U}) = 2\pi f\ [2.22\cdot 10^{-4} \exp\left(-7000\ \left(\frac{u^*}{c} - 0.031\right)^2\right) + 0.119\ \left(\frac{u^*}{c}\right)^2 \exp\left(-0.0004\left(\frac{c}{u_*}\right)^2\right)] \qquad (2.11)$$

where,

u^* - friction velocity ($k_o \times U/g$)
c - phase velocity (m/s)
k_o - von Kármán's constant (0.4)
g - acceleration of gravity (m/s^2)

Wave growth is controlled empirically in shallow water. The S20 model iterates for the solution of E at each shallow water point so that the total energy $m_o = \iint E d\theta df$ is in agreement with the depth-limited wave height prediction equation given in the Shore Protection Manual

(U.S. Army, 1977) at each time step.

Two decay terms were used by Seaconsult-1981. For no wind or following winds a term of the form $-\alpha Hm_o^4 f^4 E$ was used (Gelci and Devillaz, 1970; Karlsson, 1972). This was augmented by an additional $-BE$ term for opposing winds representing the work done by the wind against the waves (Mitsuyasu and Mizuno, 1971; Isozaki and Uji, 1973).

Directional spreading is incorporated into S20 with a cosine-squared function independent of frequency. The solution procedures are described by Hodgins et al., 1981 and Hodgins et al., 1982. This model differs from other discrete spectral models in that the refraction of wave energy is computed at every time step for every component using a Lagrangian difference scheme. The basic formulation follows the work of Abernethy and Gilbert (1974).

The S20 model was solved on the grid shown in Figure 2.25 with the following discretizations.

Space	uniform Cartesian grid $\Delta x = \Delta y = 40$ km grid size 29 x 21, 609 grid points
Time	$\Delta t = 1$ hr.
Frequency	15 frequency bins, where $f = 0.055+n(0.015)$ Hz; $n = 0,1,...14$
Direction	16 directional bins, where $\theta = n(22.5)$ degrees; $n = 0,1,...15$ relative to grid north

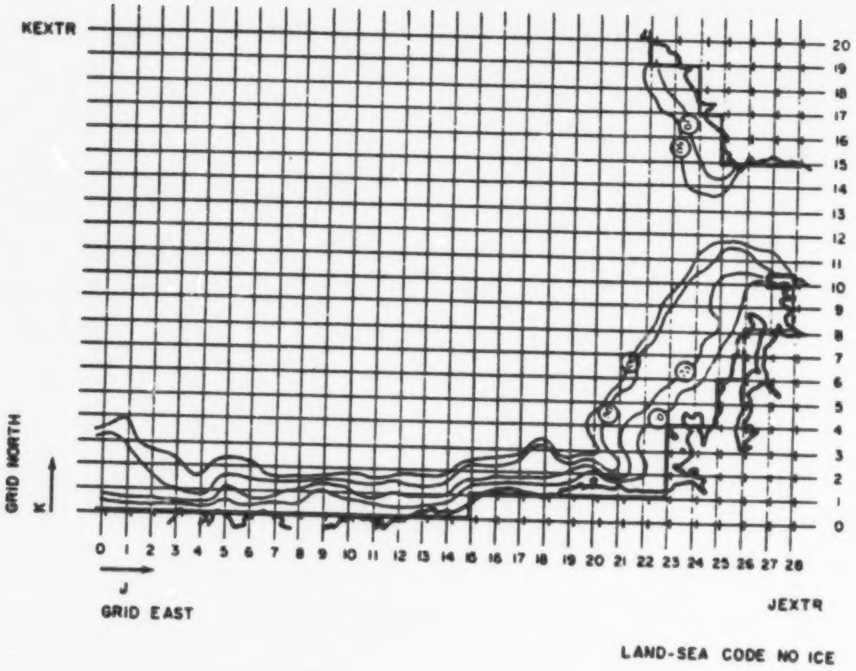


Figure 2.25 S20 model grid for the Beaufort Sea. The bathymetry is contoured in fathoms. (Source: Hodgins et al., 1982).

The 6-hourly wind fields on the 190.5 km grid were interpolated in time down to 3-hourly fields using the fitted polynomials (MEP, 1982) and linearly interpolated in time and space for the above discretizations.

Sea ice was input to the model with the most northerly nine-tenths ice edge reported by Brower et al. (1977) (Figure 2.26a) for each extreme storm hindcast. By way of a comparison, the ice distribution for the verification trial is shown in Figure 2.26b.

Since the purpose of this report is to examine extreme wind wave conditions, the storm surge model will not be described in detail. It is sufficient to note that the model used was an implicit finite difference solution to the non-linear shallow-water wave equations, developed by the Danish Hydraulic Institute and called the System 21 Mark 6 (Rodenhuis et al., 1978; Abbott et al., 1973). It was applied to the Beaufort Sea on a 20-km grid nested inside the wind-wave model grid (Figure 2.25) with a three-times finer subgrid (6.667 km) inside Mackenzie Bay. A detailed description of the solution method and application is presented by Hodgins et al., 1981.

(c) Verification

The following six storms having measured winds were used to verify the modelled winds by MEP (1982):

No.	Dates	Designation
1	September 1-2, 1972	(72-1)
2	August 9-10, 1975	(75-1)
3	August 26-28, 1975	(75-2) "prototype storm"
4	August 28-29, 1977	(77-1)
5	September 1, 1977	(77-2)
6	September 21-22, 1977	(77-3)

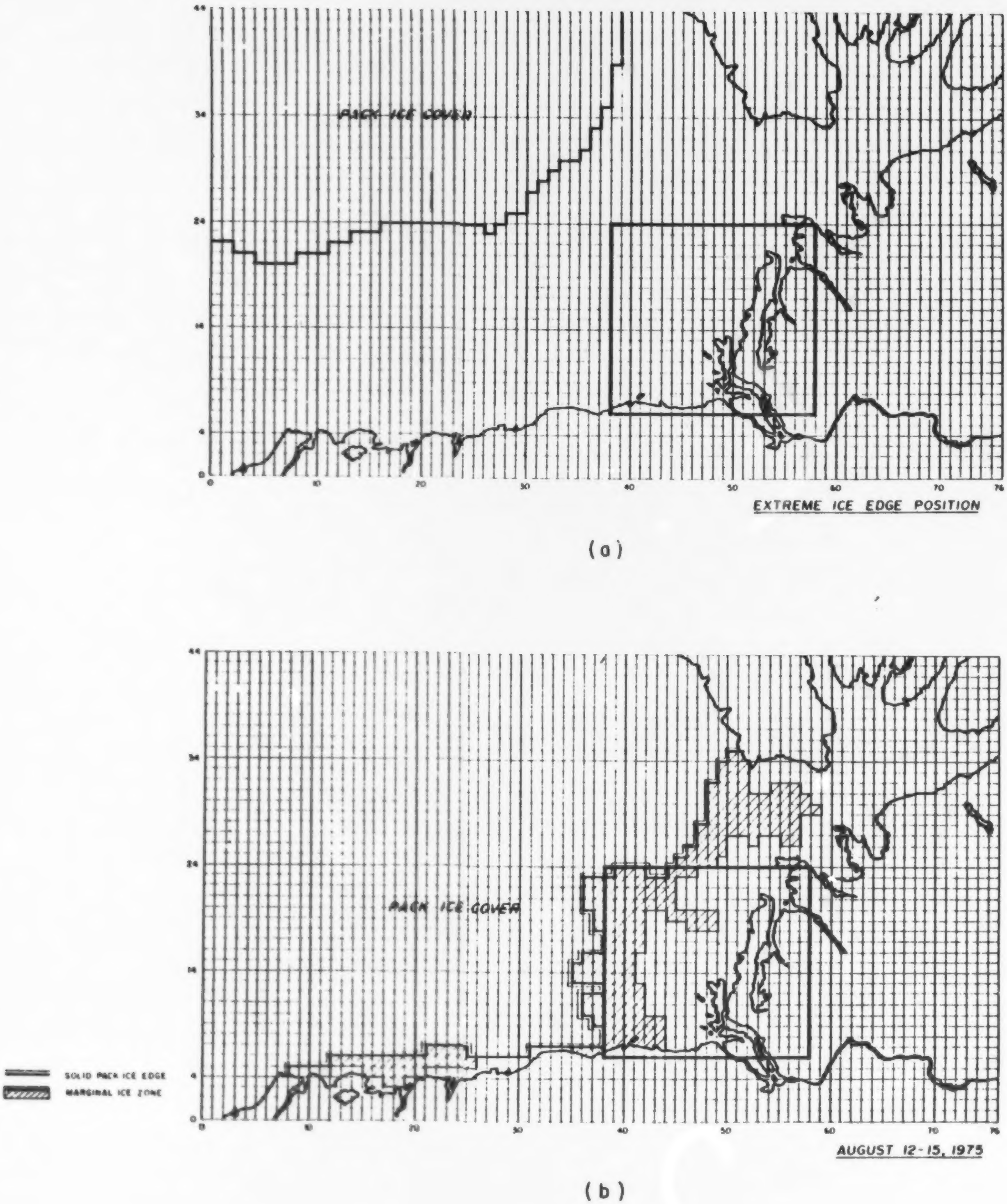


Figure 2.26 Extreme ice edge position (a) and sea ice distribution on August 12 to 15, 1975 (b) used by Seaconsult - 1981. These are shown on the 20 km surge model grid here. The resolution is only one-half of that shown for the wave hindcast model. (Source: Hodgins et al., 1981).

This was done by comparing the time series of measured speeds and directions with the modelled geostrophic and surface (19.5 m) wind data. No corrections for height of measurement or averaging time were applied in these comparisons. Sample plots, extracted from MEP (1982), are shown in Figure 2.27.

The degree to which the modelled winds reproduce the measured time series in these verification trials is noticeably poor. MEP (1982) and Hodgins et al. (1981) note that storms 72-1, 75-1 and 75-2 were large scale, low pressure systems that were analyzed in the surface weather charts; the modelled winds for these storms follow the trends of the measurements but fail to reproduce some of the temporal detail: for example, the underestimate of the peak winds in 72-1, the timing and magnitude of peak winds in 75-1, and the rapid fluctuations in wind speeds in 75-2. The remaining storms, all in 1977, were completely missed in the wind modelling procedures (see, for example, Figure 2.27d). This resulted from their absence in the pressure data due to insufficient resolution in the 381-km grid and the poor degree to which they were analyzed at the time of occurrence. The extreme spatial variability of winds in storm 77-2 (which destroyed an island under construction by Esso Resources Canada Limited) is discussed by Hodgins et al. (1981, p. 83) and shown in Figure 2.28.

Hodgins et al. (1981, pp. 44, 70-71) concluded that the modelled wind fields were not accurate enough to use as input for calibrating and verifying the wind wave model against measured wave data. The main problem was felt to be the inability of the 381-km grid of pressure data to regenerate the original pressure fields from which the gridded data were extracted. This was due to smoothing out of gradients by inadequate resolution and

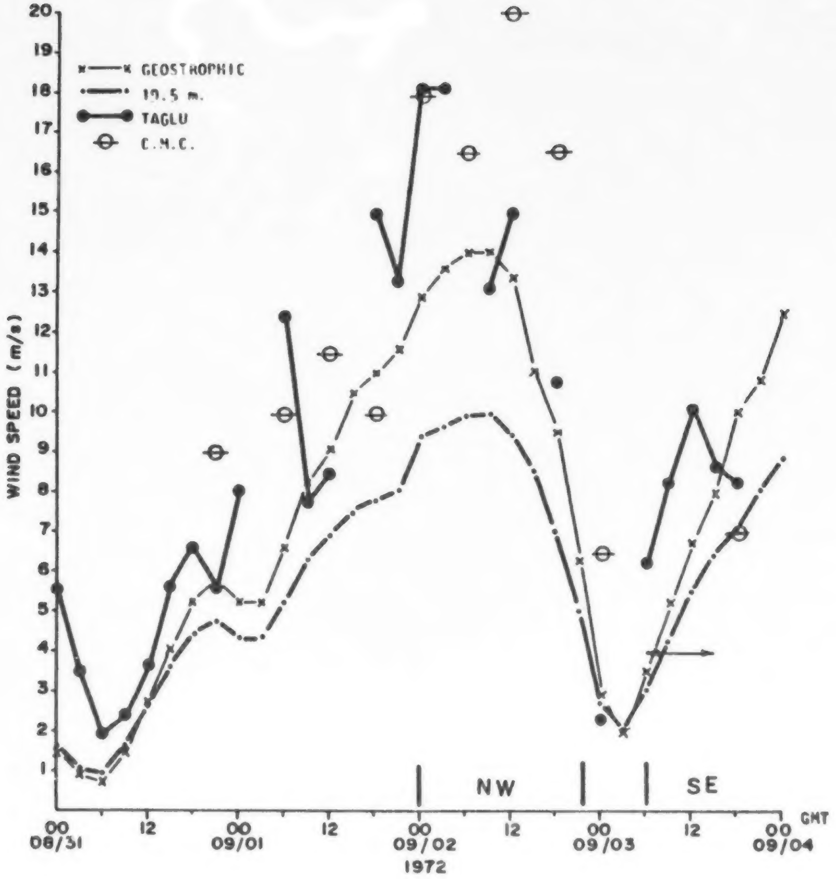


Figure 2.27a Comparison of modelled and measured winds for storm 72-1. No directional data were available. (Source: MEP, 1982).

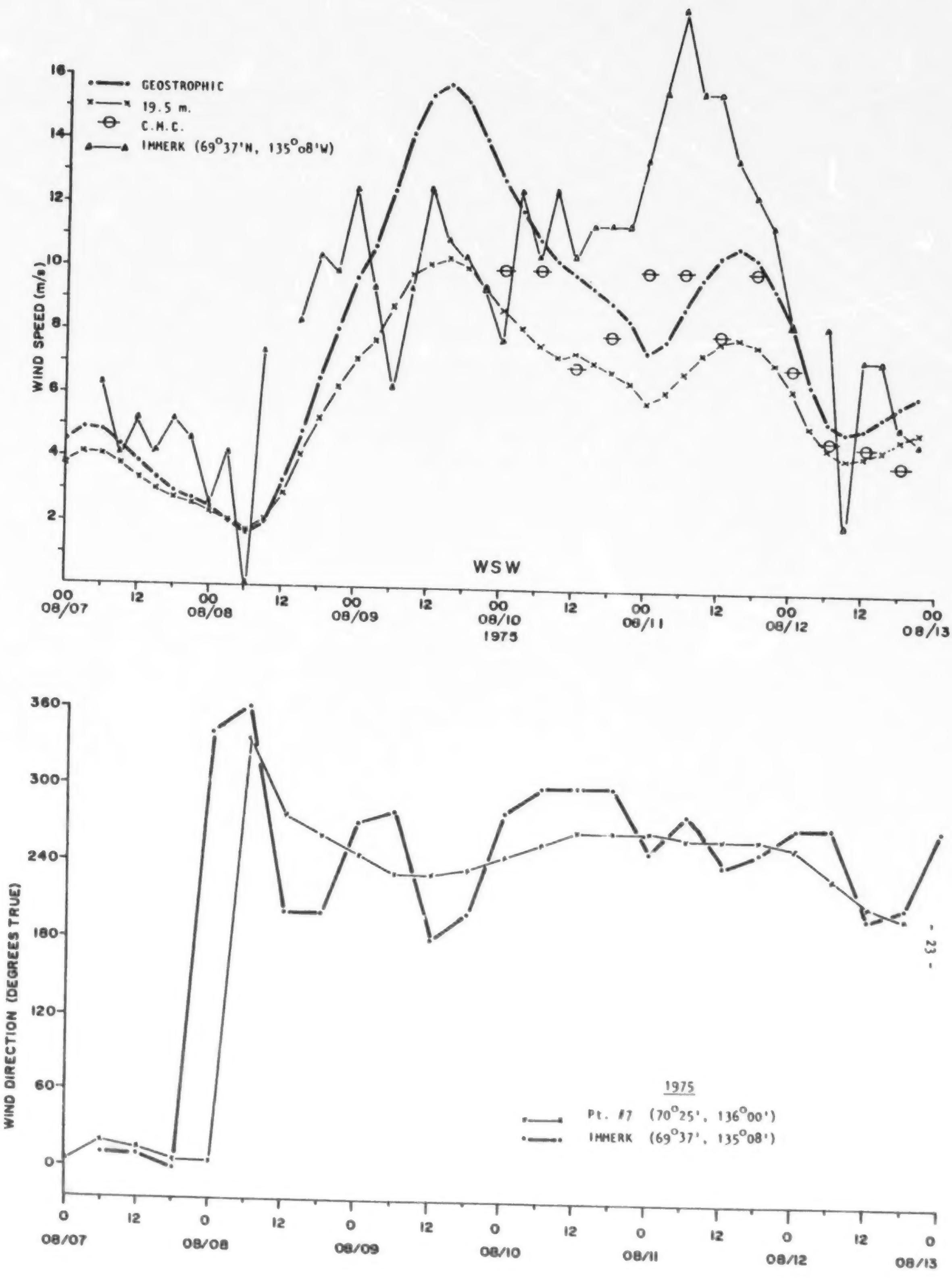


Figure 2.27b Comparison of modelled and measured winds

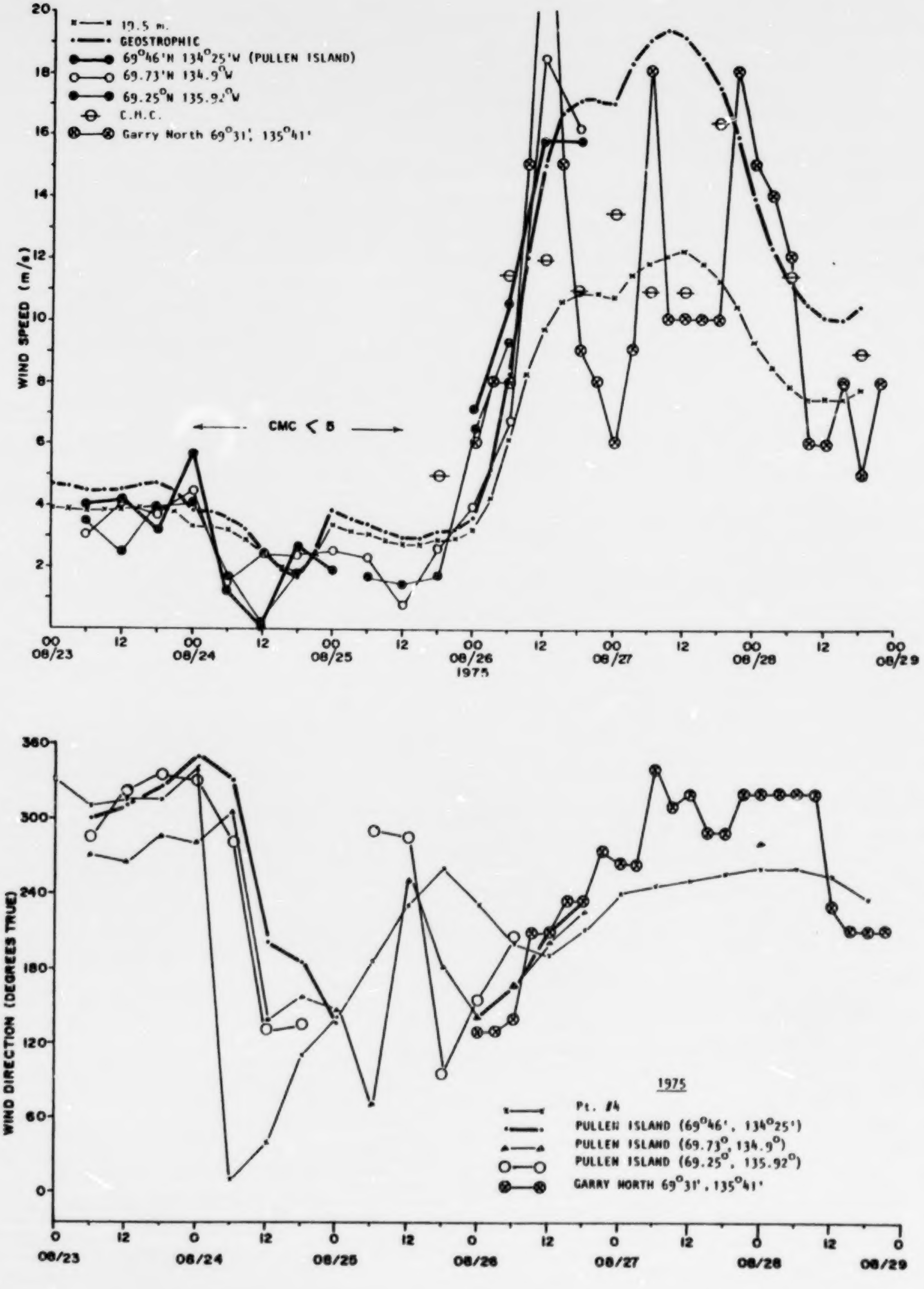


Figure 2.27c Comparison of modelled and measured winds for storm 75-2. (Source: MEP, 1982).

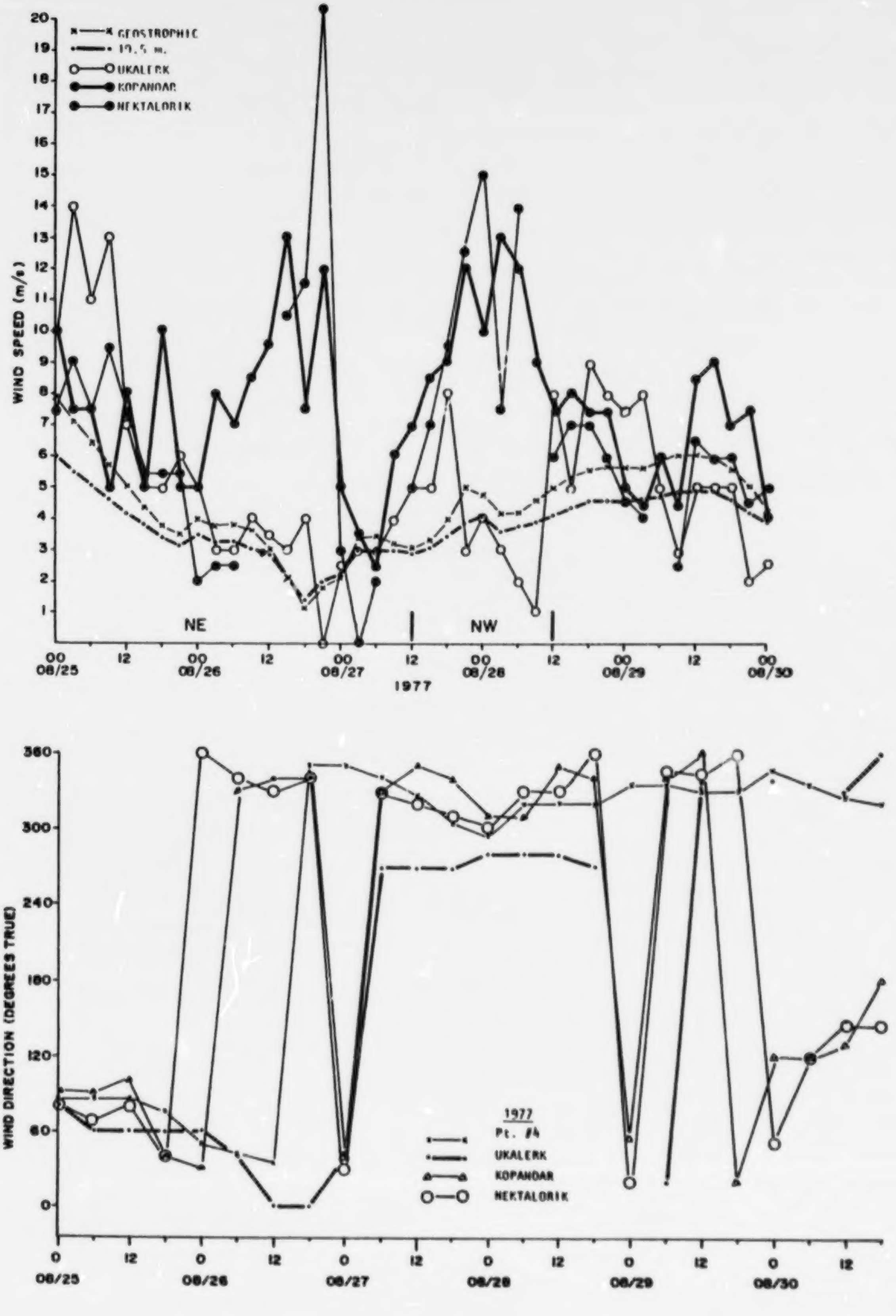


Figure 2.27d Comparison of modelled and measured winds for storm 77-1. (Source: MEP, 1982).

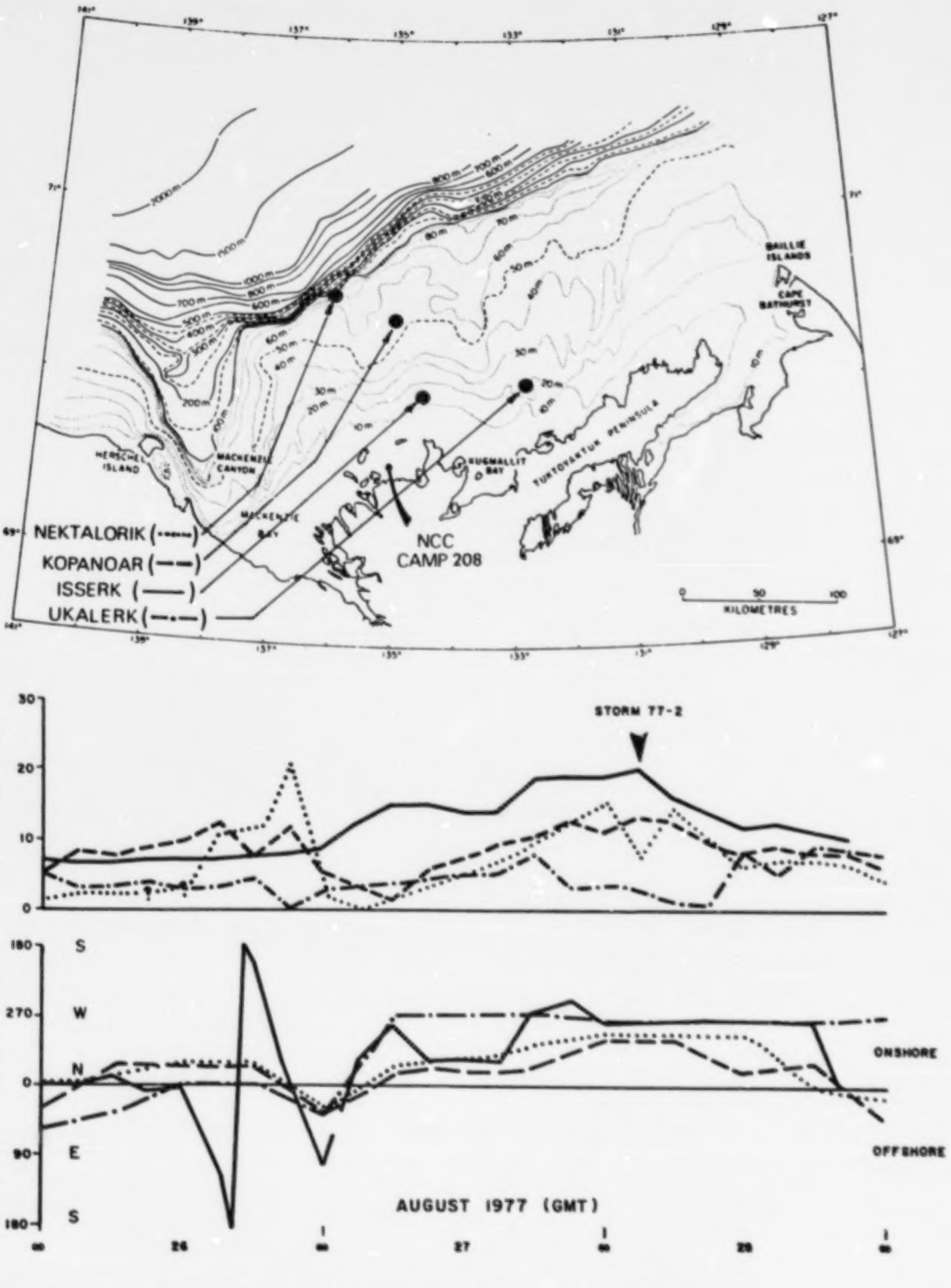


Figure 2.28 Wind speed and direction time series at four stations during storm 77-2. Data sources are MEP (1982) and Anderson (1978). (Reproduced from Hodgins et al., 1981)

poor or no delineation of smaller scale weather features.

As a result it was not possible to verify the total wind-through-to-wave modelling procedure directly. Only one verification run of the S20 model was made for the Beaufort Sea, using measured winds at NCC Camp 208 (Figure 2.28) distributed uniformly over the model grid at each time step for storm 75-1. The ice cover distribution is shown in Figure 2.26b and the time series comparison of significant wave height with Waverider data is shown in Figure 2.29. Combining this result with more extensive testing of the S20 model carried out by the Danish Hydraulic Institute in the North Sea, Hodgins et al. (1981) state that errors of ±0.6 m significant wave height are applicable to the S20 results. This figure is about 10 percent of the peak measured North Sea wave height during the reported trial.

(d) Results

The key results from the Seaconsult-1981 hindcast are shown in Table 2.12 at two of the stations, 3 and 7, for comparison with the other hindcasts discussed in this report. The return periods indicated here are those of the intensified storms; the ice edge is taken at its extreme offshore limit.

A sample directional spectrum at site 4 (Figure 2.19) in 16 m of water is shown in Figure 2.30 for the 100-year return storm; the influence of bathymetric refraction is apparent. The local wind direction is about 246° grid whereas the peak wave energy of 2.9 $m^2/Hz \cdot rad$ at 0.070 Hz corresponds to 293° grid, a reorientation of the long period wave energy produced by refraction. The high frequency lobe of the spectrum (periods between 8

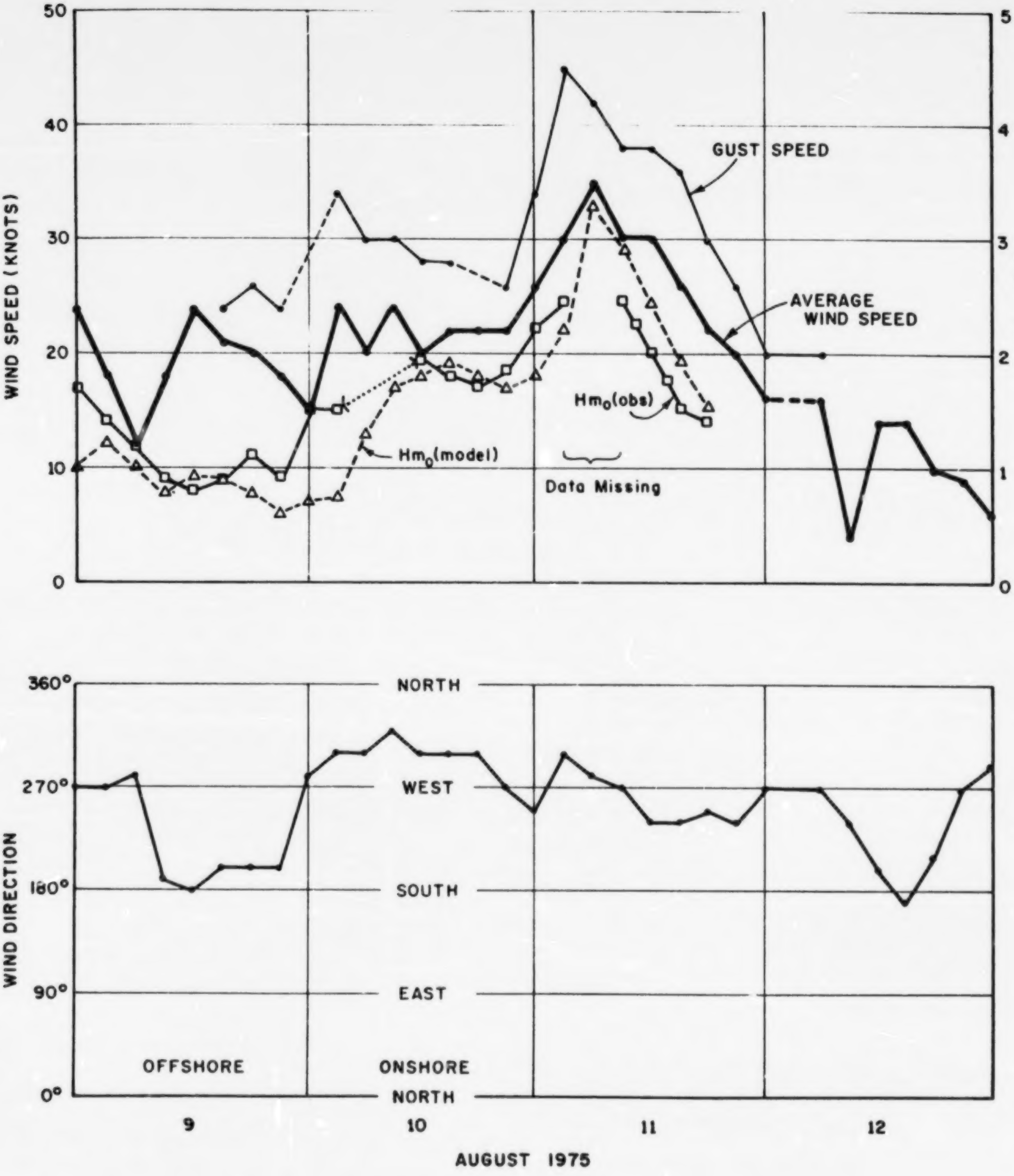


Figure 2.29 Time series of wind speed and direction measured at NCC Camp 208 together with time series of significant wave height measured at station 03 and as computed with the S20 model. (Source: Hodgins et al., 1981).

Table 2.12

Extreme wind speed and significant wave height estimates by Seaconsult - 1981.

	Return Period (yrs)	Sites	
		3	7
hourly averaged wind speed[1] (knots)	10	45	46
	20	-	-
	50	55	55
	100	59	61
significant wave height H_S (m)	10	5.5[2]	9.2
	20	-	-
	50	5.5	12.8
	100	5.5	13.2

[1] Source: MEP (1982).

[2] Wave heights were depth-limited for all storms at this site.

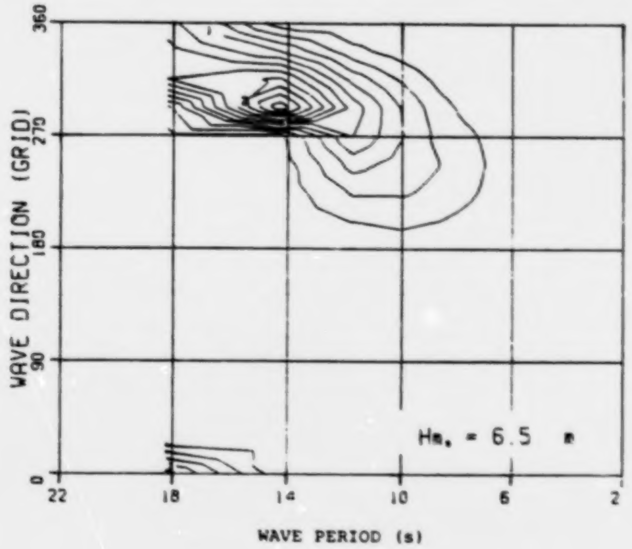


Figure 2.30 Two-dimensional energy spectrum for site 4 for the peak of storm E-3 (100-year return). Contour interval is 0.2 m^2/Hz·rad. (Source: Hodgins et al., 1981).

and 12 s), covering directions between about 225° grid to 270° grid, shows wave energy input by the local wind, largely independent of refraction.

The surface pressure map and wind vector field at the peak of storm E-3 (100-year return) are shown for reference in Figure 2.31. These correspond with the spectrum discussed above.

(e) Limitations

The major limitations to this study appear to lie with two aspects of the wind fields and the way in which the ice was treated in determining the wave height return periods. Hodgins et al. (1981) point out in their report that the inaccurracies in the wind fields modelled for the six well-monitored storm events precluded any complete verification of the procedures, and that to a certain extent this limits confidence in the final results. However, the extreme events hindcasted in this study were much more severe than normally encountered in the Beaufort Sea so that the confidence gained from modelling 3 m wave heights would not necessarily translate into the same confidence for 10 m waves. For this reason the inclusion of the North Sea verification trial was important to support the S20 wave model.

The second limitation on the wave results is the degree to which the wind modelling smooths out some of the temporal variations in the storm wind data, particularly the motion of fronts and the winds associated with them. There are two consequences to this: the highest winds in a storm tend to be underestimated and the duration of high (but not the highest in a storm) wind speeds tends to be overestimated. This is evident in Figure 2.27c for the 75-2 simulation. As a result the

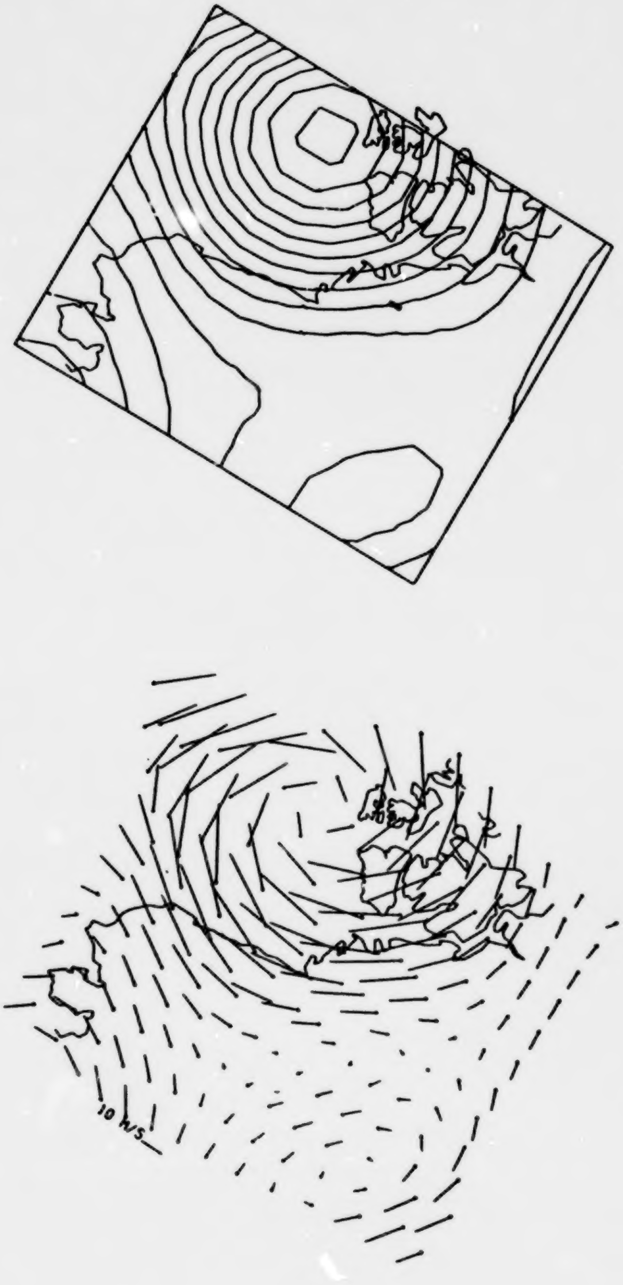


Figure 2.31 Surface pressure and geostrophic wind field for the 100-year storm in the Seaconsult - 1981 hindcast. (Plots provided by Seaconsult Marine Research Ltd. to this present study).

modelled wave heights would tend to be biased high (duration effect) and the timing of maximum heights would not correspond well with observed variations.

By treating the ice cover at its furthest offshore position the influence of fetch on limiting wave heights is essentially removed from the hindcast. Thus the probability of fetch occurrence does not enter into the calculation of the return period for the wave heights. Consequently the return periods for the storms are somewhat shorter than the return periods of the wave conditions as hindcasted in this study.

2.7 Review and Discussion of the Results

(a) Comparison of Study Results

The extreme wind speed and significant wave heights in deep water are summarized for each study in Table 2.13. The deep water site is essentially the same for each set of results because of the inherent accuracy in the parametric SMB techniques, except in the case of the Brower-1977 values. It might be argued here that because the wind distribution was derived from Point Barrow and Barter Island measurements that the wave heights would be more applicable to the Alaskan waters than to Mackenzie Bay. Brower's wind speed extremes are also higher than the last four hindcasts directed specifically at Mackenzie Bay.

The wave height results could scarcely be less in agreement with each other. It would appear that little confidence can be placed in the Brower estimates because of the neglect of sea ice in deriving the wave height distribution following Thom's (1973b) approach. For similar reasons, the stated return periods of wave

Table 2.13

Summary of extreme wind speed
and significant wave height estimates.

	Wind Speed (knots)				Source of Wind Data
	Return Period (years)				
Study Name	10	20	50	100	
ISR - 1971	70	79	90	98	Surface Charts
IRC - 1974	41	42	43	45	Surface Charts Measured Winds Inuvik
Dames & Moore - 1974	54	59	65	67	Measured Winds Sachs, Parry, Tuk
Brower - 1977	62	67	75	81	Measured Winds Barrow, Barter
Hydrotechnology - 1980	44	49	56	59	Measured Winds Tuk
Seaconsult - 1981	46	49[1]	55	60	381 km Grid Pressure Data
	Deepwater Significant Wave Height (m)				
ISR - 1971	7.9	8.8	9.8	10.5	
IRC - 1974	3.1	3.4	3.7	4.0	
Dames & Moore - 1975	5.2	6.3	8.0	9.8	
Brower - 1977	11.0	12.8[1]	15.0	17.0	
Hydrotechnology - 1980	4.8	5.5	6.5	7.3	
Seaconsult - 1981[2]	9.2	10.6[1]	12.8	13.2	

[1] Interpolated (Figure 2.32).

[2] Return Periods correspond to the design storm; ice is taken at furthest offshore limit.

heights produced by the design storms in Seaconsult's study are too low due to the influence of ice cover on the probability of such wave heights occurring. This problem was examined in a later study by Hodgins et al. (1982) and will be discussed in Chapter 4.

The basic method of obtaining the extreme wave heights in three of the remaining studies--IRC-1974, Dames & Moore-1975 and Hydrotechnology-1980--was similar: from histories of wind information the largest wave height in each open water season was calculated and these sample maxima were extrapolated in time assuming a certain distribution function. Now it is clear that the quality of a wave hindcast is primarily determined by the quality of the input wind information. Although different sources of wind data were used in each of these three studies consistency of the analysis for wave height maxima dictates that in overlapping years each investigator should select the same storms. If the performance of the wave hindcast models were greatly different it would explain why the same meteorological events might be found in each report producing different maximum wave heights; however, the three studies used SMB or modified-SMB methods and the same source of ice data. Therefore it is reasonable to expect the seasonal maximum wave height to be produced by the same storm in each study.

The deep water significant wave heights and the corresponding storm dates for these studies are shown in Table 2.14. There are four years when all three overlap, 1970 to 1974. In 1970 all investigators selected the same storm occurring on September 14 although the predicted values of H_s differ by 35% of the mean. Also in 1972 IRC and Hydrotechnology selected the September 2nd storm--known to have been a severe event producing

Table 2.14

Summary of H_s and storm dates -- annual maxima.

Year	IRC 1974 H_s (ft)	IRC 1974 Storm Date da/mo	Dames & Moore 1975 H_s[1] (ft)	Dames & Moore 1975 Storm Date da/mo	Hydrotechnology 1980 H_s (ft)	Hydrotechnology 1980 Storm Date da/mo
1956			10.0	22/08		
57			7.0	16/09		
58			7.5	29/09		
59			9.5	05/09		
60			13.5	07/10		
61			7.5	24/08		
62	10.1	31/08	13.5	14/09		
63	12.0	16/10	17.0	04/10		
64	11.8	04/09	8.0	10/09		
65	12.8	28/09	8.5	27/09		
66	6.6	10/09	7.5	23/10		
67	7.8	04/10	8.5	11/10		
68	9.6	07/09	7.5	23/10		
69	10.6	16/08	6.5	23/09		
70	17.0	14/09	14.0	14/09	12.0	14/09
71	10.1	03/08	9.0	04/10	8.7	22/08
72	14.0	02/09	9.5	03/10	13.6	02/09
73	10.0	03/10	8.5	13/10	5.7	14/10
74			8.0	09/08	0	ice bound
75					8.3	27/08
76					8.4	11/08
77					9.8	28/08
78					7.6	24/08
79					6.5	05/08

[1] The Dames & Moore values are for class 1 and 2 storms only so that the comparison with other studies comprises storms of the same general type.

large surges (Hodgins et al., 1981)--and hindcasted it in agreement at $H_S \approx 14$ feet. Dames & Moore (1975) did have this storm in their analysis for the year, although it was not the worst, and for it they predicted $H_S = 5.5$ ft based on Sachs Harbour winds. In 1973 Dames & Moore and Hydrotechnology agree on the storm but IRC selected a different event with much higher wave heights than the others. In 1971 none of the investigators agreed.

In the eight overlapping years between 1962 and 1969 IRC and Dames & Moore agree in only one year, 1965 but differ by 40% of the average hindcasted wave height. In the other seven years there is no concensus on the worst wave-producing storm and in six of them Dames & Moore (1975) found two to four storms per season giving higher waves than IRC. In each case these more severe storms had ENE winds based on Cape Parry or Sachs Harbour data. In selecting the Dames & Moore storms to be included in Table 2.14, events in their Class 3 (ENE winds) were omitted. This makes the comparison with IRC meaningful because all IRC storms selected were for westerly or northerly winds (see Table 2.2). We also note that in five of the 12 years the worst storm in the IRC study was not even identified in the Dames & Moore Class 1 or 2 storms.

The Dames & Moore study relied almost exclusively on Sachs Harbour and Cape Parry wind observations; only in four storms were Tuktoyaktuk data used to give overwater winds for hindcasting. This study consistently identified the worst storms and wave heights in Class 3, i.e. with ENE winds. This finding sharply contrasts with all other studies which, for Mackenzie Bay, conclude that winds along the Alaskan coastline or northwesterlies off the ice accompanying deep low pressure systems produce the highest wave heights. This, together with the wind speed distributions shown in Figure 2.9, indicate that Sachs Harbour and Cape Parry winds are not representative of storm winds pertinent to hindcasting wave heights in Mackenzie Bay. The failure of the Sachs Harbour winds to model the September 2, 1972 storm, as noted above, particularly illustrates this point.

The IRC-1974 data included in Table 2.14 were the deep water wave heights for site 3 before depth and ice sheltering modifications were incorporated. These values correspond with straight-line fetches and as such are directly comparable with the results of the other two studies.

One of the interesting aspects of Table 2.14 is that the range of annual maxima for H_s is nearly the same for IRC-1974 and Dames & Moore-1975; i.e. from about 6.5 to 17.0 feet. Hydrotechnology have a lower range of values, from 5.7 to 13.6 feet. The data from Table 2.14, together with Dames & Moore-1975 results from all storm classes (as noted earlier they consistently found the worst storm each year corresponded to ENE winds, and including their Class 3 data gives a set of sample maxima containing more large values than shown in Table 2.14), have been fitted with an FT-I distribution in Figure 2.32. These data have all been reduced in the same way using the plotting position formula:

$$P(H_{s_i}) = 1 - \frac{i - 0.44}{N + 0.12} \qquad (2.12)$$

and reduced variate

$$r_i = -\ell n\,(-\ell n\, P(H_{s_i})) \qquad (2.13)$$

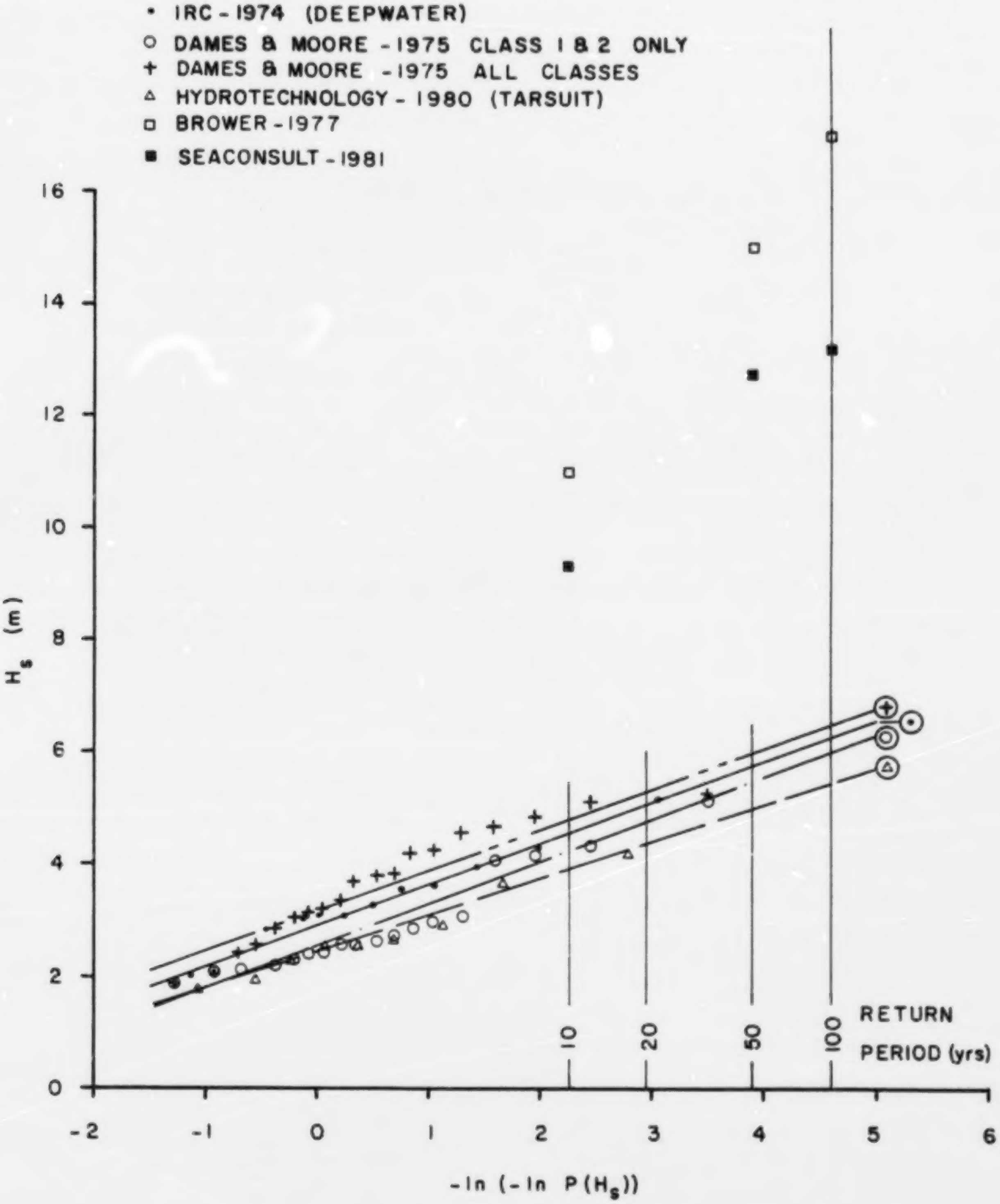


Figure 2.32 Comparison of extreme value distributions (FT-I) for each hindcast study (except ISR - 1971).

For comparison the Brower-1977 and Seaconsult-1981 values are also shown. The Hydrotechnology-1980 results are the lowest in wave height consistent with their lower range of annual maxima. These data were taken for site 1 (Tarsuit) because they were available to this study; the H_s values at Kopanoar are generally greater than at Tarsuit which, had they been used, would bring the Hydrotechnology distribution more into agreement with the other curves. However, considering the usual level of statistical significance of all of these distributions once they are extended past twice the length of their database, the 50 and 100-year return period values are not very different (range of 2 m) considering the large differences in wind speed and storms selected by each investigator.

Thus we find that despite the fundamental differences between the outcome of the wind analysis and annual maxima for H_s for each study, they predict about the same 50 and 100-year return period values for extreme wave height. This shows that we cannot judge between these three studies for reliability on the basis of the extreme statistics treatment of the annual maxima, nor on the sets of annual maxima themselves. Other criteria are required which are discussed in the next section.

(b) Final Assessment

For the reasons stated at the beginning of this section the Brower-1977 results are considered to be unrealistic because the influence of ice cover on the wave height distribution was neglected; specifically, the return periods given are too short for the reported wave heights. The ISR-1971 hindcast suffers from a lack of documentation. Based on the description in their report (ISR, 1971) the treatment of the wind data seems cursory and the methods and results are unsubstantiated by verification. Compared with later hindcasts it rates a lower level of confidence, but we must note that it did attempt to treat the independent influences of storm wind and ice-restricted fetch to derive joint cumulative wave height distributions.

Hodgins et al. (1981) and Baird and Hall (1980) both comment on the small scales of spatial variability found in the wind and wave fields in Mackenzie Bay. Of the remaining four studies, Seaconsult-1981 attempted to model both the spatial and temporal variability of the wind fields to predict the variations in the wave fields. The other three studies, IRC-1974, Dames & Moore-1975 and Hydrotechnology-1980 all considered the Beaufort Sea to be an enclosed basin of small size compared with that of the storm-generated wind fields. Using this assumption storms were parameterized by spatially uniform winds; Hydrotechnology-1981 incorporated temporal changes in wind speed and direction but the remaining studies used only one direction and a storm duration. A judgment between these three hindcasts requires an assessment of how successful this assumption was and how accurate the wave hindcast procedures were in light of it.

By using Sachs Harbour and Cape Parry winds to represent both the Western Amundsen Gulf and Mackenzie Bay, Dames & Moore-1975 found the largest wave heights of the three parametric studies. Since these wave heights mostly corresponded with ENE winds, a condition found in none of the other hindcasts and unsubstantiated by an analysis of winds measured in Mackenzie Bay, it seems to warrant less confidence than the IRC-1974 and Hydrotechnology-1980 studies. In fact the application of Sachs Harbour, Cape Parry and Tuktoyaktuk wind measurements indiscriminantly to sites as far as 400 km apart is highly questionable.

The overlapping comparison of winds and waves between the IRC and Hydrotechnology studies is too limited to ascertain if one is more reliable than the other in terms of the wind parameterization. It appears that the definition of storms and derivation of winds is about equally good for the uniform wind field assumption. The real difference lies in the application of the SMB technique. The IRC-1974 hindcast used an effective fetch calculation based on ice sheltering that greatly reduced their deep water wave heights in many years. This procedure is not well verified in their report, and has the result of lowering their extreme wave height predictions for 50 and 100-year return periods.

Hydrotechnology-1980 verified their straight-line fetch assumption (within reasonable bounds considering the single point-source wind) and, moreover, modelled approximately the changes in wind direction during severe storms. Thus through use of a better parametric model and the most appropriate winds for Mackenzie Bay, the results presented by Hydrotechnology-1980 appear to be the most reliable.

The Seaconsult-1981 study found, as have others (Cardone et al., 1979; Harding and Binding, 1978) that a machine-based procedure of deriving two-dimensional wind fields from the 381-km grid point pressure data does not adequately capture essential details. In particular the motion of fronts, and variations in wind speeds associated with these, to which the wave field is sensitive, are not well modelled. This is made worse in the Beaufort Sea by the sparseness of reporting stations north of the coastline. Their design storms are judged to be possible meteorological events but severe in the range of observed storms due to the long durations of high winds. Because the ice was modelled at its furthest position offshore the wave heights reported by Seaconsult must be interpreted as the most severe conditions which can occur in storms having 50 or 100-year return periods.

3 MEASURED WAVE DATA

3.1 Data Disposition

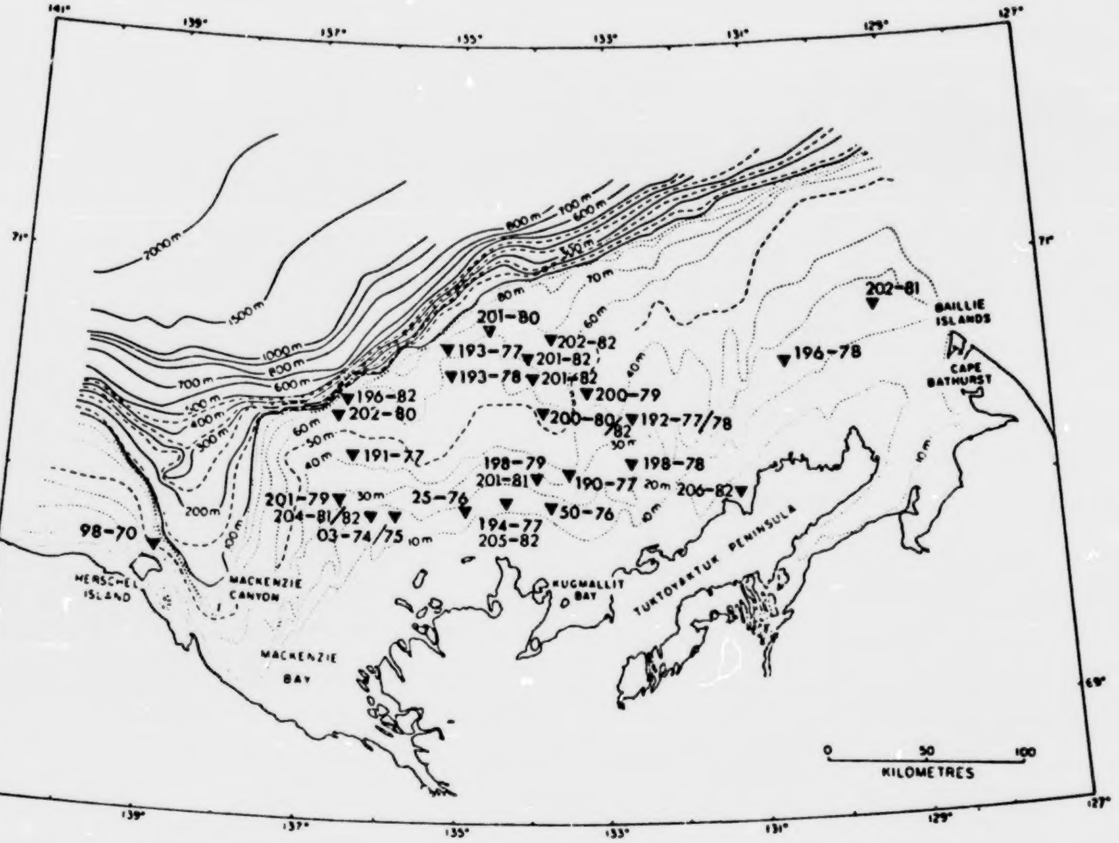
The spatial and temporal distribution of measured wave data in the Beaufort Sea is illustrated in Figure 3.1. These data are bounded on the east by Cape Bathurst and by Herschel Island to the west. Data from U.S. sources further west along the Alaskan coastline have not been examined in this report and do not feature in the hindcast studies reviewed in Chapter 2.

These data were measured exclusively with Datawell Waverider buoys deployed in accordance with Marine Environmental Data Service (MEDS) standards. The first stage processing was carried out by MEDS and the data have all gone through their standard quality control checks. Thus the Beaufort Sea data are of uniform reliability.

The duration of records varies considerably. Instrument deployments were influenced by both ice conditions and the activities of the drilling vessels on which the data acquisition equipment was installed. In Figure 3.1 the 1982 data specifications are provisional. At the time of writing, final details were required from the agencies that carried out the field programs.

The data recording format also varies. In most instances it was 20 minutes every 3 hours with little continuous recording during storms. The 1982 data are 20 minutes every hour with continuous recording at some stations for Hm_0 exceeding 2 m.

These wave data are important in two respects. They allow statistical estimates of extreme wave heights to



Stn. No.	Name	Location N Lat	Location W Long	From D/M	To D/M	Year	Depth (m)
98	Herschel Is	69-39	139-00	01/08	30/08	70	50.0
03	Tuktoyaktuk	69-53	135-57	26/08	30/08	74	21.0
03	Tuktoyaktuk	69-53	135-57	08/08	06/09	75	21.0
25	Pullen NW	69-59	134-59	08/08	09/10	76	15.0
50	Pullen NE	69-57	133-50	08/08	08/10	76	15.0
190	Gulf-1	70-04	133-38	15/08	13/10	77	33.2
191	Gulf-2	70-08	136-25	16/08	11/10	77	42.7
192	Canmar-1	70-11	132-45	07/08	02/10	77	34.1
193	Canmar-2	70-24	135-06	07/08	01/10	77	64.0
194	Isserk	69-58	134-26	11/08	16/09	77	14.0
192	(Ukalerk)	70-10	132-44	22/07	04/10	78	31.0
193	(Kopanoar)	70-23	135-06	02/09	04/10	78	57.0
196	Tarsuit	70-34	130-51	31/08	01/09	78	27.0
198	Issungnak	70-04	132-27	04/08	13/08	78	24.0
198	Issungnak	70-04	132-27	19/08	15/10	79	24.0
200	Nerlerk	70-32	133-21	03/08	10/09	79	46.0
201	Tarsuit	69-58	136-36	13/08	18/09	79	30.0
200	Nerlerk	70-24	133-54	11/08	22/09	80	50.0
201	Tarsuit	70-34	134-35	16/08	13/09	80	60.0
202	Explorer IV	70-18	136-36	15/08	07/09	80	60.0
201	Issungnak	70-05	134-26	28/07	31/08	81	27.0
202	Kilannak	70-46	129-21	05/08	14/08	81	25.0
204	Tarsuit	69-53	136-11	13/08	15/08	81	20.0
196	Nerlerk	70-25	133-27	22/07	25/08	82	52.0
196	Orvilruk	70-22	136-32	01/09	29/09	82	58.0
201	Irkaluk	70-35	134-14	22/07	21/08	82	58.0
201	Aivark	70-26	133-59	01/09	29/09	82	62.0
202	Kennalooak	70-44	133-50	22/07	26/07	82	71.0
202	Kennalooak	70-41	133-58	NO DATA		82	70.0
204	Tarsuit	69-53	136-00	30/07	20/08	82	20.0
204	Tarsuit	69-51	136-00	01/09	29/09	82	20.0
205	Ittyok	69-57	134-30	03/08	25/09	82	14.0
206	McKinley Bay	- -	- -	07/08	06/10	82	-

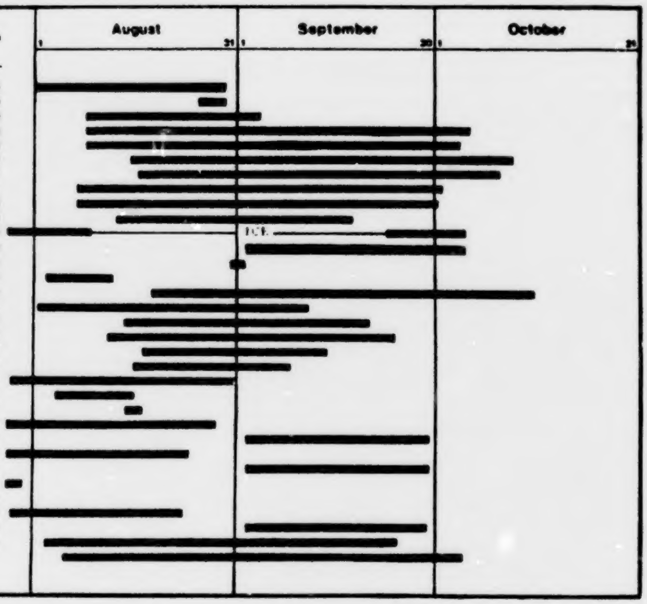


Figure 3.1 Spatial and temporal distribution of Waverider data in the Beaufort Sea. 1970 to 1982.

be made from measured storm maximum wave heights, and they are essential to verifying hindcast model performance. Results from a study of extreme wave heights based on the Waverider data are discussed in the next section. This is followed by an assessment of the utility of the Waverider data, and some earlier visual data, for model verification.

3.2 Extreme Wave Height Estimates

In 1981 Esso Resources Canada Limited commissioned a study of normal and extreme wave conditions based on observed data (Hodgins and Dal-Santo, 1981). Extreme value estimates, which are of interest here, were made by sampling the time series of significant wave height for recorded maxima in time blocks of various lengths. These were then fitted with two extreme value distribution functions which in turn were used to calculate the 20, 50 and 100-year return period heights.

The sensitivity of these extreme wave heights to the type of distribution, to the distribution fitting parameters, and to methods of blocking the data were examined in some detail.

Two distribution functions were selected:

the Fisher-Tippett type I

$$P(H<H_o) = \exp\left[-\exp-\left(\frac{H_o-A}{B}\right)\right] \qquad -\infty<H_o<\infty \qquad (3.1)$$

and the Weibull distribution

$$P(H<H_o) = \begin{cases} 1 - \exp\left[-\left(\dfrac{H_o-A}{B}\right)^C\right] & H_o > A \\ 0 & H_o < A \end{cases} \tag{3.2}$$

with B>0 and C>0.

The time series of significant wave height for the data shown in Figure 3.1 up to and including 1980 were scanned for records that contained the largest wave heights and sufficient continuity of data to sample in different time blocks over the season. The following ten stations were selected:

Station No.	Name	Year	Duration (Days)
03	Tuktoyaktuk	1975	29
50	Pullen NE	1976	61
191	Gulf-2	1977	56
193	Canmar-2	1977	55
193	Canmar-2	1978	33
198	Issungnak	1979	57
200	Nerlerk	1979	68
201	Tarsuit	1979	66
201	Tarsuit	1980	58
202	Explorer IV	1980	53
		Average =	54 days

The extreme value analysis was then carried out with three different time blockings:

4-days, $\tau = 0.036$

7-days, $\tau = 0.063$

14-days, $\tau = 0.125$

where τ is the sampling rate in years based on a 16-week season. Within each period for a given time blocking, the maximum value of significant wave height was determined and these values from all ten Waverider records were ordered into the extreme value set $\{\bar{H}\}$. A four-day block was selected as the lower limit so that the chance of extracting two wave height maxima in adjacent blocks that were produced by the same storm (and hence not truly independent samples) was minimized. This choice was governed by the observation that the severest storm-generated sea-states in the Beaufort Sea seldom exceed 3 days in duration. Fortnightly blocking is the longest practical period that could be used in order to obtain a sufficient number of sample wave heights (about 38 values from the ten time series). These three blockings allowed examination of the sensitivity of the extreme wave heights to the number of samples to which the probability distribution was fitted.

The probabilities for the extreme value set $\{\bar{H}\}$ were calculated from the plotting position formula

$$P_i(H<\bar{H}_i) = 1 - \frac{(i-u)}{(N+v)}, \quad i = 1,2,\ldots,N$$

where u,v are constants which depend on the chosen distribution. The values for the reduced variate $r_i = (H_O-A)/B$ were calculated from

$$r = -\ell n\ [-\ell n\ P]$$

for FT-I, and

$$r = [-\ell n\ (1-P)]^{1/C}$$

for the Weibull distribution.

To improve the least-squares fit of the data to the theoretical distributions, a lower limit cut-off $\bar{H}_{min}$ of 1.6 m was imposed which in effect gave zero weighting to maximum significant wave heights less than this cut-off value. This cut-off produced the best fit for both distribution functions.

A sample of the optimal fits is presented in Figure 3.2. The blocking length is 7 days and the distribution parameters u,v,C together with the R^2 correlation coefficient are shown in the figure. A comparison of results from the two distributions in Table 3.1 reveals that there is virtually no difference between the two theoretical models.

Based on the fitting tests Hodgins and Dal-Santo (1981) found that:

> The extreme wave heights derived from both distributions were not sensitive to the blocking factors and for the Beaufort Sea Waverider data 7-day and 14-day blocks were nearly equivalent.
>
> The extreme wave heights were sensitive to the choice of independent distribution parameters (u,v,C) and to the lower bound constraint, $\bar{H}_{min}$. They found, however, that it was possible to obtain the same extreme wave heights to within ±0.05 m in the range 4.1 to 4.7 m with either the FT-I or Weibull distributions with suitable choices for these parameters. Since the R^2 values from the curve fitting procedure for both distributions were in agreement to within 0.2% (0.99 ± 0.002), and the curves provided a good linear fit to all data in $\{\bar{H}\}$, there was no basis in the Beaufort Sea data for choosing one distribution over the other.
>
> The optimum fitting parameters were given as:

	FT-I	Weibull
H_{min}	1.6 m	1.6 m
u	0.44	0.44
v	0.12	0.47
C	-	1.25

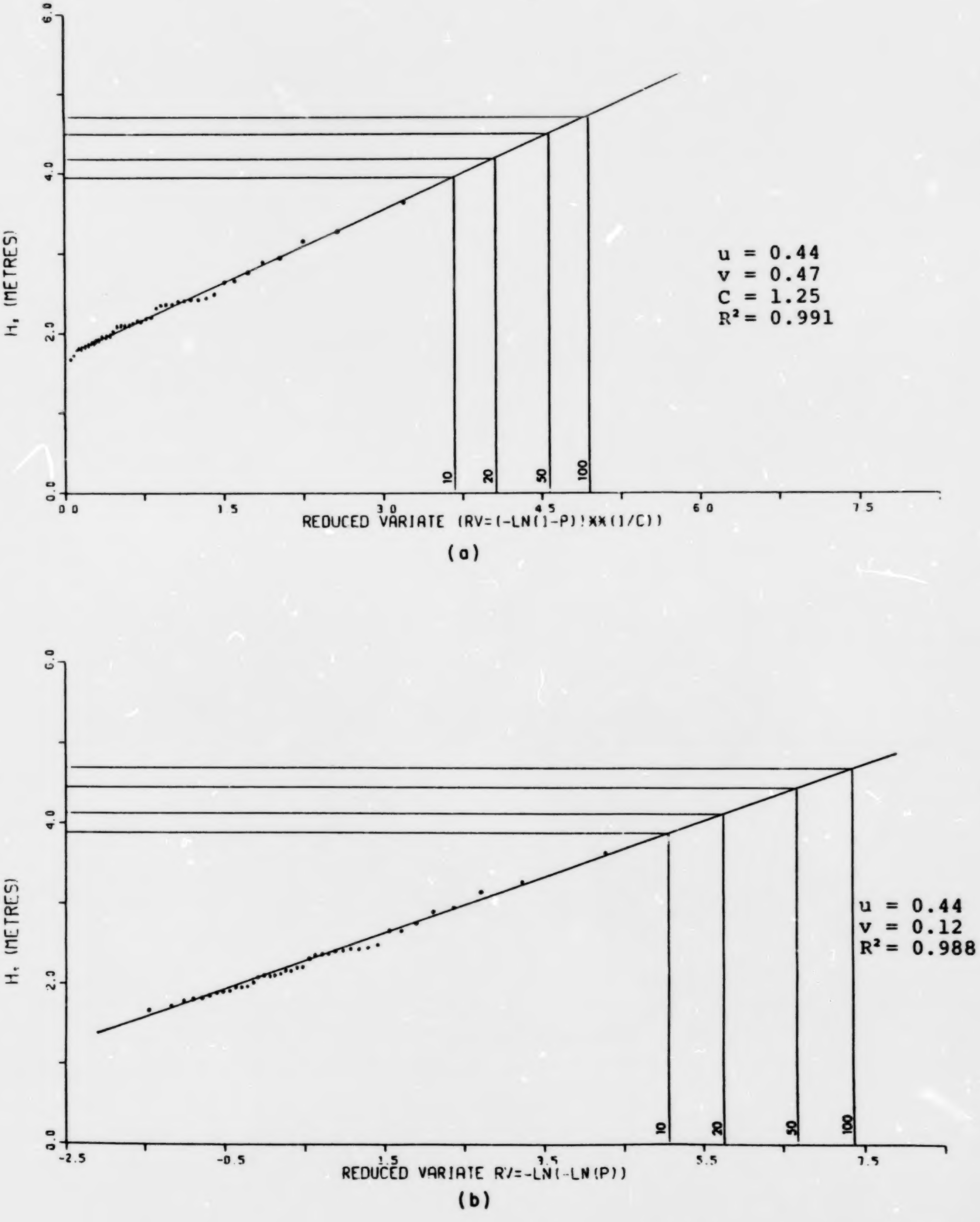


Figure 3.2 Optimum Weibull (a) and FT-I (b) distributions for the Beaufort Sea data. (Sources: Hodgins and Dal-Santo, 1981).

Table 3.1

Comparison of results from the optimum FT-I and Weibull Distributions. (Source: Hodgins and Dal-Santo, 1981).

Distribution	u	v	C	$\bar{H}_{min}$	R^2	Hm_o (m) Return Period (Yr) 20	 50	 100
FT-I	0.44	0.12	-	1.6	0.988	4.12	4.44	4.69
Weibull	0.44	0.47	1.25	1.6	0.991	4.17	4.48	4.71

Blocking factor = 7 days

R^2 - correlation coefficient between the straight-line fit and the observed data.

The data base was only six years long and hence was most probably too short to give reliable 50 and 100-year return period values.

It is also noted that the wave height maxima were selected without reference to any storm classification and contained wave height values produced both by large scale extratropical cyclones and by intense small scale Arctic lows. Thus the sample contained wave heights arguably from two different populations. The effect this may have had on the distributions and the extreme wave heights was not investigated.

As shown by comparing Tables 3.1 and 2.13, the extreme wave heights are similar to only the IRC-1974 results. As discussed in Chapter 2 the IRC estimates lie below those of the Dames & Moore-1975 and the Hydrotechnology-1980 studies mainly because of the treatment of the ice and effective fetch, and shoaling factors. In general it seems that the use of longer wind time series (10 to 19 years) with hindcasted wave heights captures a larger proportion of extreme events than were present in the six years of measured wave data. In such circumstances hindcasting from wind data is a more reliable approach than attempting to extrapolate measured wave data.

3.3 Utility of the Wave Data for Hindcast Verification

In approaching a hindcast of the Beaufort Sea there are several major storms that should be considered, either in the selection of "design" storms or as events to be modelled. For some of these storms there are wave data, instrumental or visual, which can be used to verify model performance. Unfortunately, there are also some limitations in the data, which are not apparent in Figure 3.1, that make certain storms less useful than others for these purposes. These storms, and the wave data available for them are reviewed here to assist future studies of severe wave conditions in the Beaufort Sea, and to illustrate the utility of the Waverider data for model validation and understanding the impact of the small-scale Arctic storms. We begin with a discussion of the September 13-14 storm in 1970 which produced according to visual estimates, the largest observed wave height to date.

(a) September 13-14, 1970

As inferred from storm surge damage and debris lines (Reimnitz and Maurer, 1979) this storm was one of the most severe in memory, producing surge levels of 2 to 3 m around Mackenzie Bay. It was, perhaps, of equal severity with another major event in September, 1944 (DPW, 1971; ISR, 1971; Reimnitz and Maurer, 1979). A Waverider was deployed near Herschel Island (Figure 3.1) during the summer; however, it was removed on August 30, so that no instrumental recordings were made during the storm 14 days later. However, DPW (1971) reported offshore maximum wave heights of 30 feet (9.1 m) with accompanying winds of 31 m/s sustained for four hours. This observation represents the only report of a wave height over 6 m in the Beaufort Sea and for this reason assumes an important role in attempting to verify hindcast wave data. Consequently efforts were directed at establishing the reliability and correct interpretation of this wave height.

Direct contact with Public Works Canada personnel involved in the 1970 work at Herschel Island failed to reveal the source of the reported wind and wave data. However, it was known that the CSS Hudson, out of Bedford Institute of Oceanography, was in the Beaufort

Sea during this storm. The ship's log was acquired for documentation of the visual wave observations together with the wind and position data. These are plotted in Figure 3.3. The ship was in the eastern portion of the study area and from it the maximum observed wave height H_o (considered about equal to a significant wave height) was 5 m with accompanying winds of about 40 to 45 knots. The ship's log also records that during the 13th and 14th of September the ship was operating close to the ice edge, although the entry is not precise concerning the ice cover.

Further discussions with Dr. B. Pelletier, Geological Survey of Canada, the Chief Scientist on the cruise confirmed that the ship did work in heavy seas during the storm, with wave heights of about 25 feet (7.6 m) estimated by him using the vessel for reference. Since this type of observation is, again, roughly equatable with a significant wave height, then such heights exceeding 5 to 7 m can be substantiated.

The surface analysis chart shown in Figure 3.4 (ISR, 1971) for 12:00 GMT on September 14 places the Hudson near the low pressure centre, and shows further that the strongest winds were most likely on the western side of Mackenzie Bay. Thus it is reasonable to expect higher waves there than were observed on the Hudson. However, we note that DPW's (1971) reported winds (sustained 56 knots for four hours) and the ice-limited fetch (Figure 3.5) of about 250 to 300 km produce H_s values of 17 to 20 feet (5.2 to 6.1 m) by the SMB method. Any more conclusive analysis is limited by the lack of overwater wind data.

The observations suggest that significant wave heights of 5 to 7 m did occur during the storm with the possi-

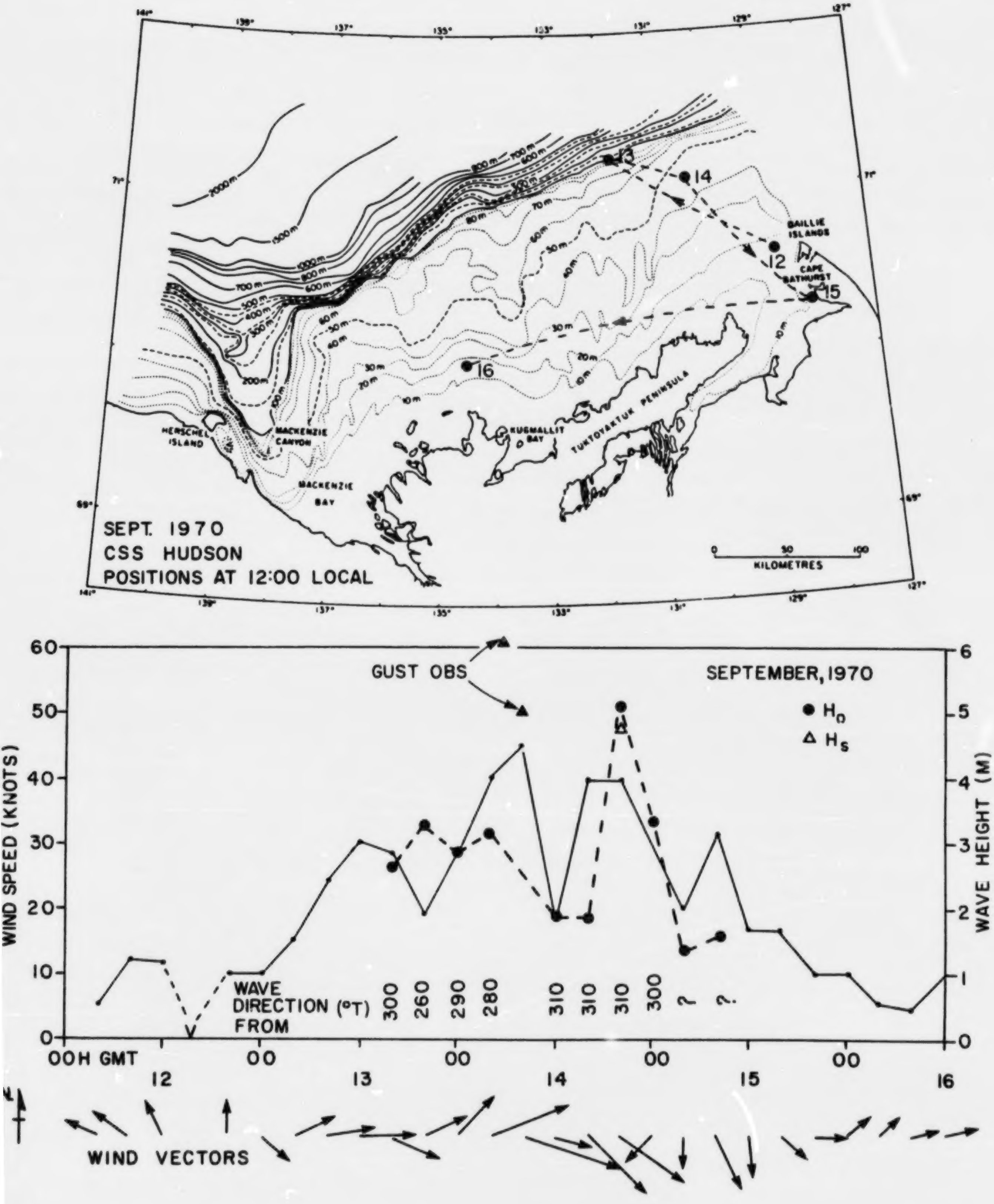


Figure 3.3 C.S.S. Hudson data during the Sept. 13-14, 1970 storm in the Beaufort Sea.

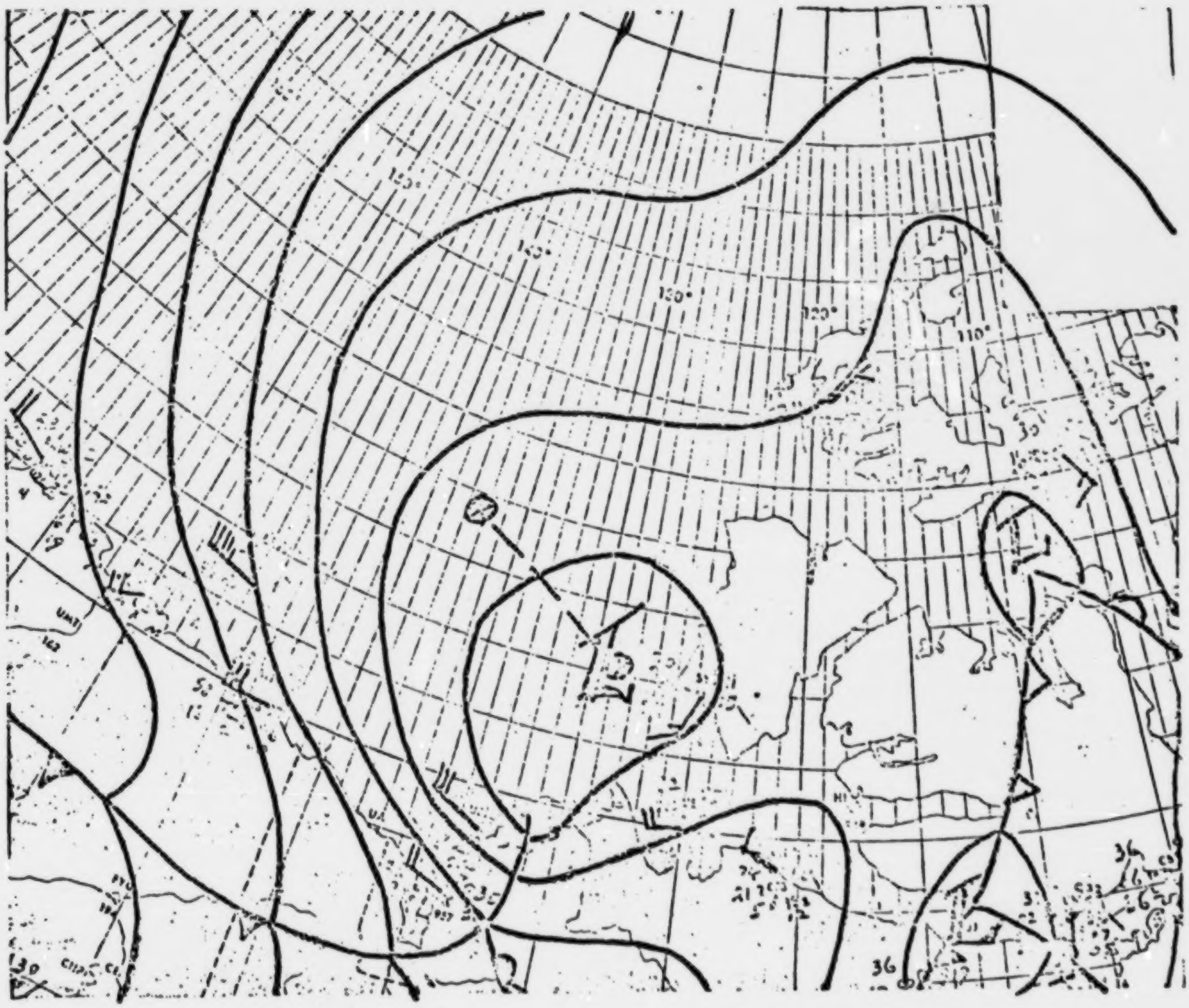


Figure 3.4 Surface analysis chart for Sept. 14, 1970 12:00 GMT. (Source: ISR, 1971).

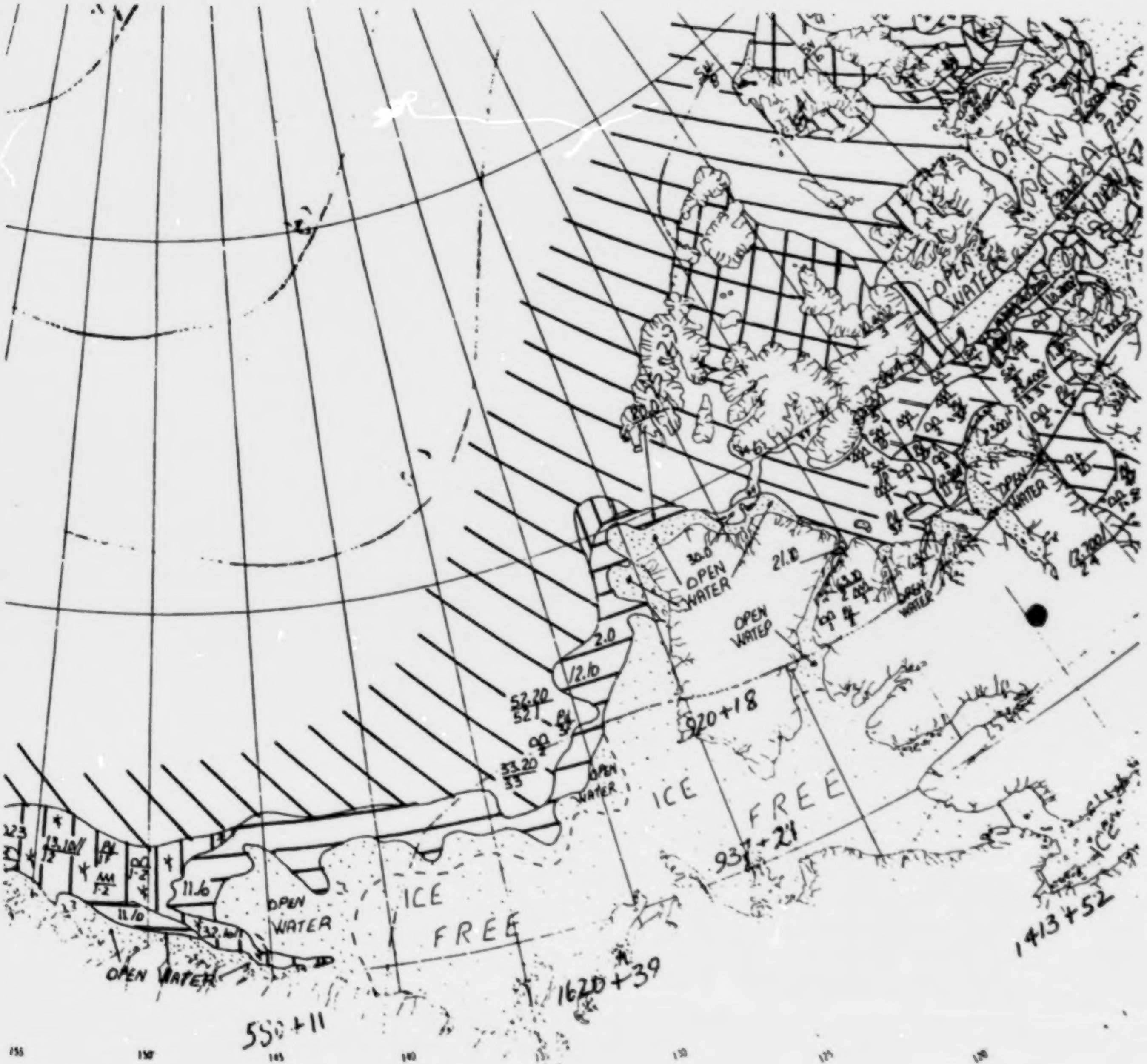


Figure 3.5 Ice conditions on Sept. 10, 1970.
(Source: Ice Climatology, AES).

bility of 7 to 8 m significant heights at the storm peak. The correct interpretation of the DPW report is, therefore, most likely as a maximum wave height and not a significant wave height.

(b) September 01-02, 1972

The surge measurements made during this storm (Henry, 1975; Hodgins et al., 1981) and the analysis of the meteorology (MEP, 1982) show that this was a comparatively severe event but not to the degree of the September 1970 storm. No wave measurements were made during this event so that while it is useful for verifying surge model response, it cannot be used to validate hindcast wave data.

(c) August 10-11; August 26-28, 1975

Two intense storms crossed the Beaufort Sea in August 1975 at times when Waverider 03 was operational. Due to transmission difficulties, however, the wave data right at the peak of each storm were lost. Because the recording format was 20 minutes every 3 hours, there are 6-hour gaps where, by inference from the wind histories, the maximum wave heights would have been expected. This greatly reduces the utility of the Station 03 data for model verification.

(d) The 1977 Season

Five Waveriders were deployed in 1977 which was a comparatively active sea-state year. In the Seaconsult-1981 hindcast three events were selected for verification purposes:

- August 26-28, 1977 (during which Esso Resources Canada Ltd. suffered severe damage to one of its islands);

- September 1, 1977;

- September 21, 1977.

Except for Station 194 (Isserk) the time series of significant wave height (Figure 3.6) show that data coverage of these events was good. However, the specification of the overwater winds for all three of these storms but particularly the first on August 26-28 gave the Seaconsult and Hydrotechnology hindcasts difficulty. This was due to the strong spatial variability and intensity of the winds.

The wave height time series for the late-August storm also show how variable the sea state response was. Referring to Figure 3.1 for station positions and comparing the time series shows a strong east to west gradient in both maximum wave heights and persistence of large waves. Over a distance of about 160 km, Station 192 on the east recorded the weakest response and Station 191 on the west measured the maximum wave height and longest duration of high waves. The September storms mentioned above show a more uniform response across the deployment area than the August event, but it is clear that capturing the spatial structure of the winds is important to accurately model the wave conditions.

The lack of instrumental data for the most severe storms in the Beaufort clearly limits the confidence which can be placed in hindcasts of these particular events. It is therefore important to continue making Waverider

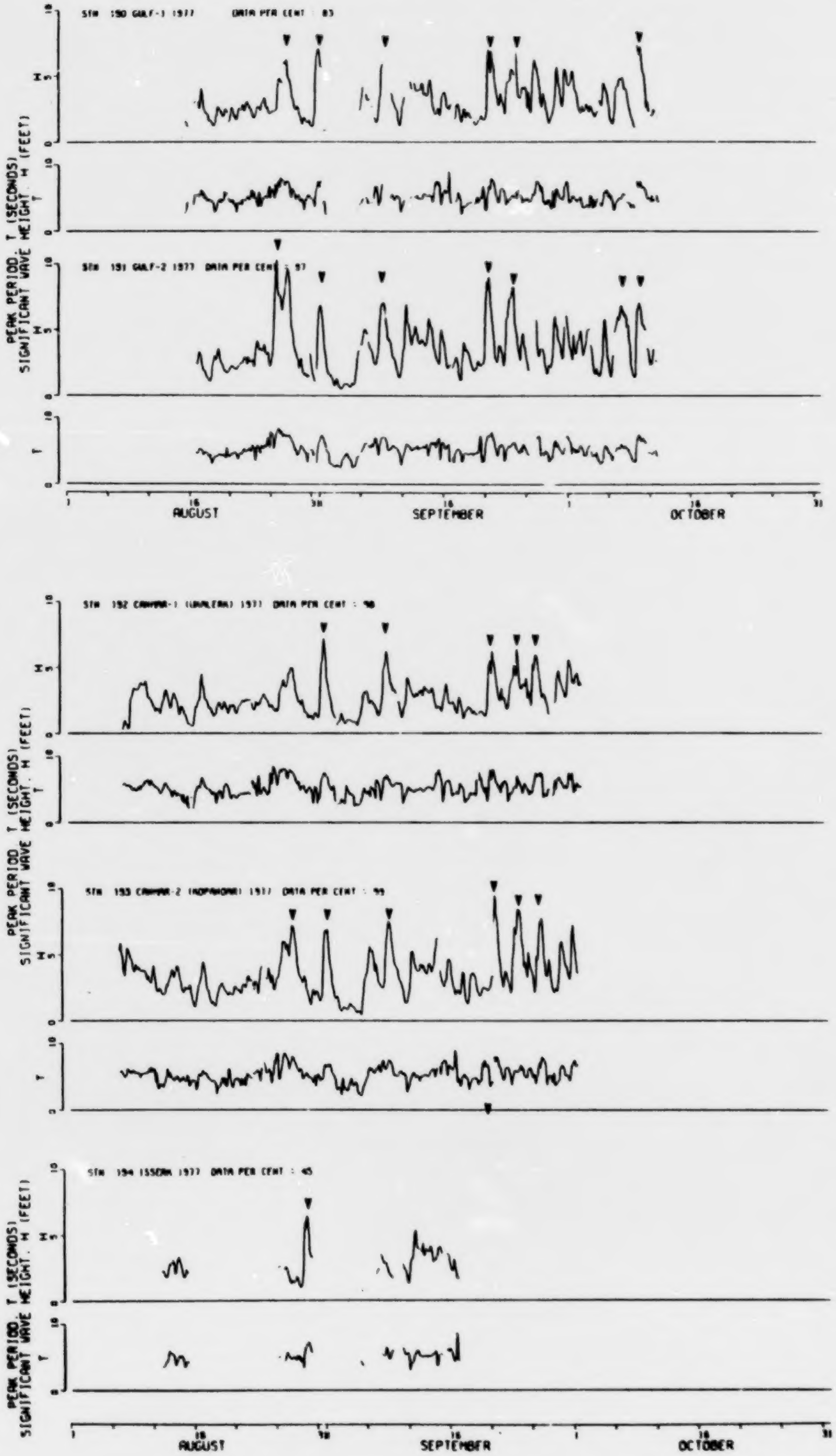


Figure 3.6 Time series of significant wave height and peak period for all Waverider data in 1977

recordings with the best possible resolution of storms to provide verification data for hindcast models and to provide insight into the degree of resolution required to model small scale storms.

4. RECENT WORK ON THE DESIGN STORM APPROACH

As noted in Section 2.6 wave conditions were hindcasted in the Seaconsult-1981 study for storms, synthesized from an actual event on August 26-28, 1975, with return periods of 10, 50 and 100 years. The ice was taken far enough offshore that it did not affect the wave heights; wave conditions were effectively limited by the storm durations. As a result the return periods of the storms when carried over directly to the wave heights, do not reflect the probability of ice moving far enough offshore to allow duration-limited waves to be generated.

To quantify the fetch probability distributions and to better classify the design storms a study, reported by Hodgins and Harry (1982), was commissioned by Esso Resources Canada Limited in May, 1982. This work is summarized here, together with a discussion of how a design storm can be specified for wave conditions with a selected joint probability of occurrence.

4.1 Storm Classification

Severe storms capable of producing strong onshore winds were compiled from 12 years (1970-1981) of surface and 500 mb analysis chart data for the months of July to October. These were classified by trajectory and the probability of occurrence of a storm in each class was determined in bi-weekly periods. This provided one part of the equation for determining the joint probability of the wave heights.

Four selection criteria were used to identify severe storms:

- the low must have a closed cyclonic circulation implied by at least one closed pressure isobar;

- the system must have an identifiable history, as a low pressure centre or as a trough, for at least 24 hours;
- the system must have geostrophic winds of 25 knots or greater at one point in its history; and
- the system must cause westerly quadrant winds in the southeastern Beaufort Sea during or immediately following its passage over the area, with upper level support for weather systems found in the critical region shown in Figure 4.1.

Storms were included in the initial selection which were marginal in satisfying these criteria so that no potentially important events would be omitted. This produced 140 storm systems distributed as shown in Figure 4.2 (total sample). A subsample was made on a synoptic meteorological basis, focussing on severe events characterized by strong pressure gradients at the surface and 500 mb, oriented to give strong NW onshore flows in Mackenzie Bay. Forty-three such storms were selected (Figure 4.2), distributed monthly as follows:

Month	Total Number of Severe Storms (All Trajectories)
July	9
August	15
September	12
October	7
Total	43

The storm trajectories were mapped as shown in Figure 4.3; the open circles are 6 hours apart and the surface

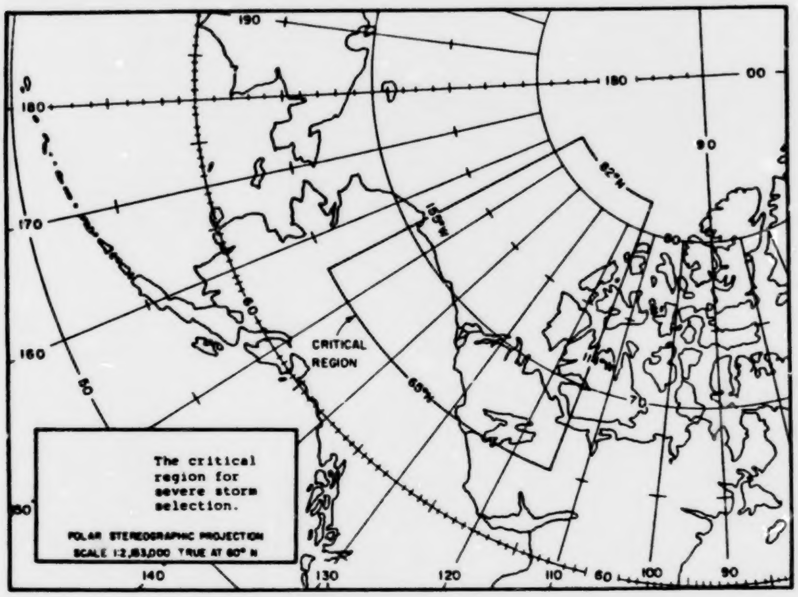

190
180
180
00
90
170
160
150
140
130
120
110
100
90
80
70
60
60
62°N
65°N
155°W
115°W
CRITICAL REGION
The critical region for severe storm selection.
POLAR STEREOGRAPHIC PROJECTION
SCALE 1:2,153,000 TRUE AT 60° N

Figure 4.1 Critical region defining severe storms. (Source: Hodgins and Harry, 1982).

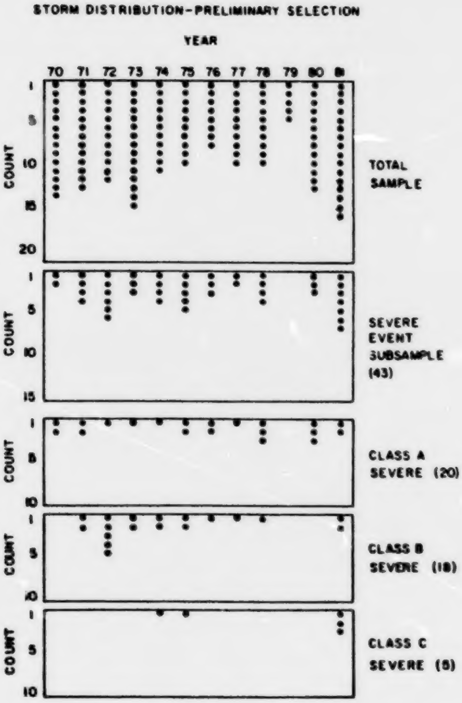
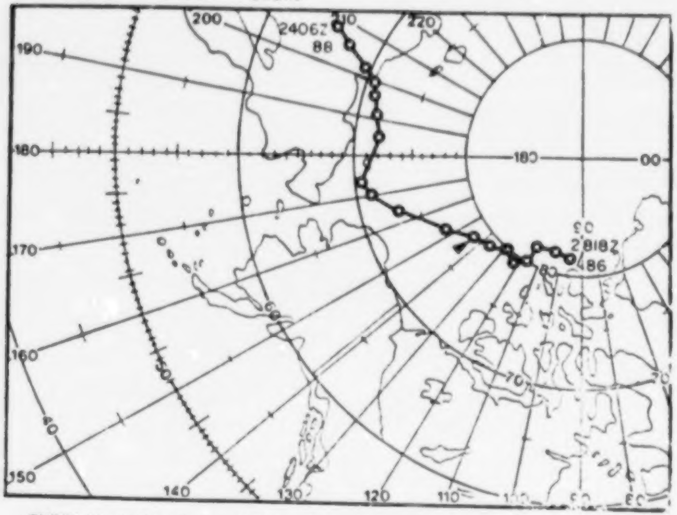


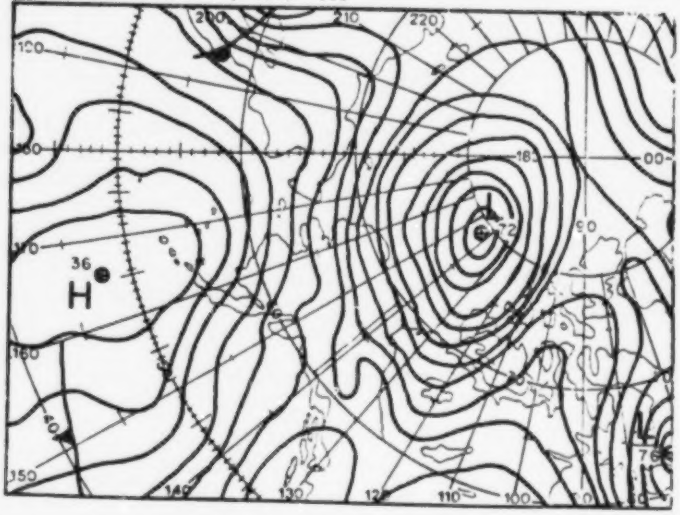
Figure 4.2 Distribution of storms over the 12-year

AUGUST 24-28, 1975

TRAJECTORY 2406Z - 2818Z



SURFACE AUGUST 27, 1975 00Z



500 mb AUGUST 27, 1975 00Z

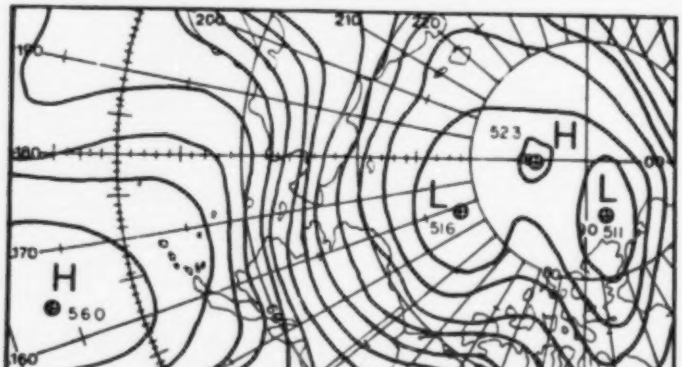


Figure 4.3 Storm trajectory, surface and 500 mb charts for the August 26-28, 1975 storm. (Source: Hodgins and Harry, 1980)

and 500 mb facsimile charts are at about the time of maximum onshore winds.

Hodgins and Harry (1982) concluded that the analysis of severe storms by trajectory revealed two principal classes or populations. Class A storms impact on the Beaufort Sea from the north or north-northwest, with trajectories across the polar ice pack (see Figure 4.4). The severe storm that caused considerable coastal damage on September 13, 1970 was in this class. Storms moving from west to east more or less paralleling the Alaskan coastline were designated as Class B storms; the prototype storm (August 26-27, 1975) chosen for the Seaconsult-1981 hindcast was of this type. The composite of all extreme storm tracks, by storm class, is shown in Figure 4.5.

As illustrated in Figure 4.2, the interannual variability of Class A and B storms is not large, recognizing the small sample size, and thus basing their probabilities of occurrence on the 12-year sample period is acceptable. The relative monthly distribution of severe storms in each class is shown in Figure 4.6; neither Class A nor B is uniformly distributed.

Figure 4.7 contains the central pressure statistics and illustrates that on this basis the two classes must be regarded as equally severe. However, it was noted that the likelihood of a Class B storm during the months of greatest open-water exceed that of Class A and furthermore, that the orientation and trajectory of Class B storms produce long-duration winds over the longest available fetches. From these two observations Hodgins and Harry (1982) concluded that the Class B storms are more severe and that the prototype storm of August 26-27, 1975 (storm 75-2 in the Seaconsult-1981 hindcast)

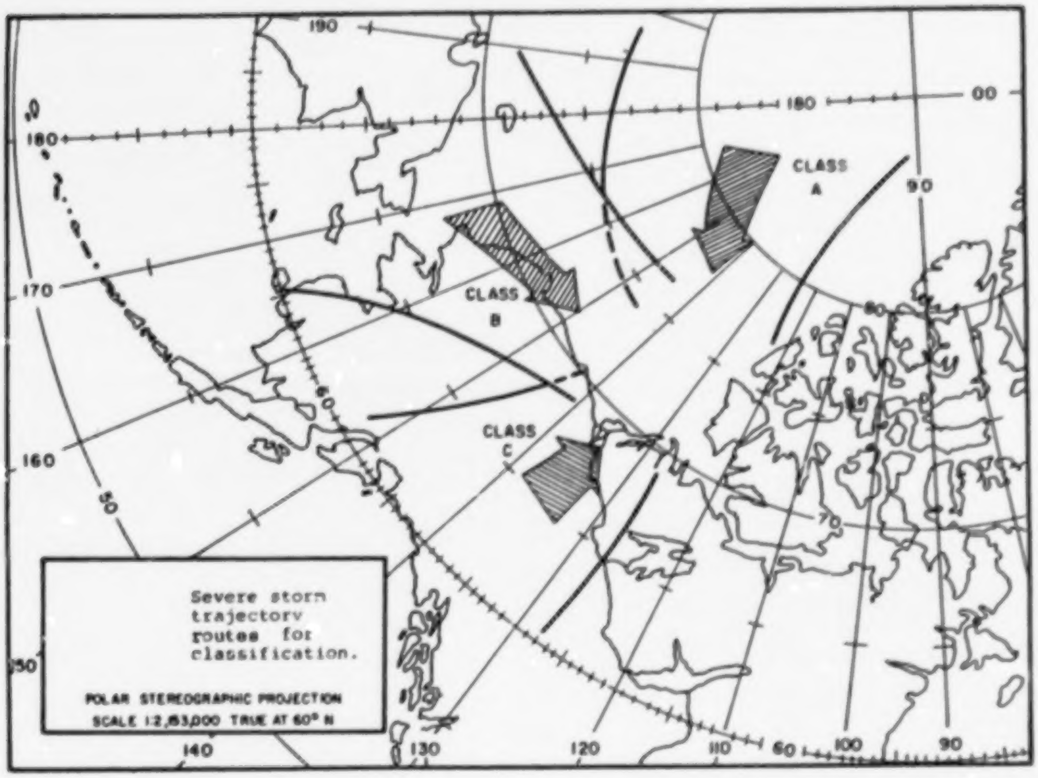
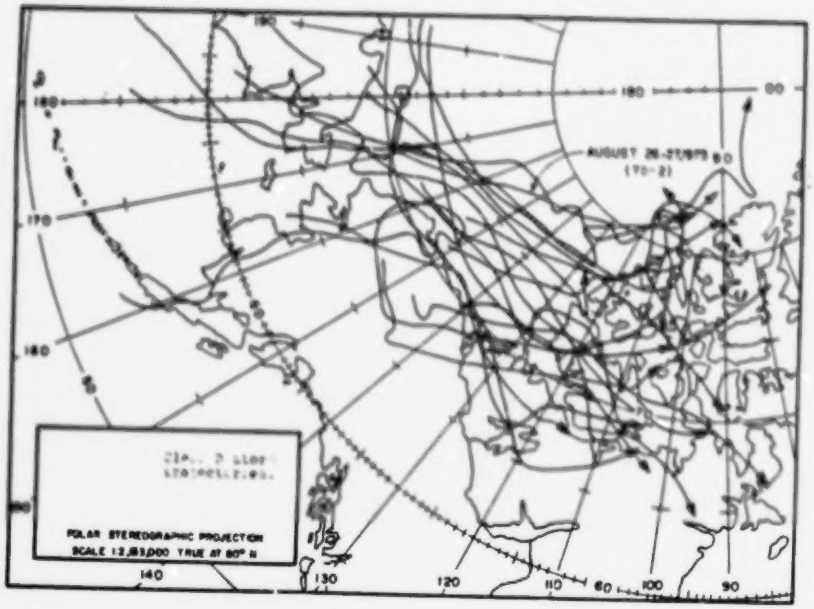
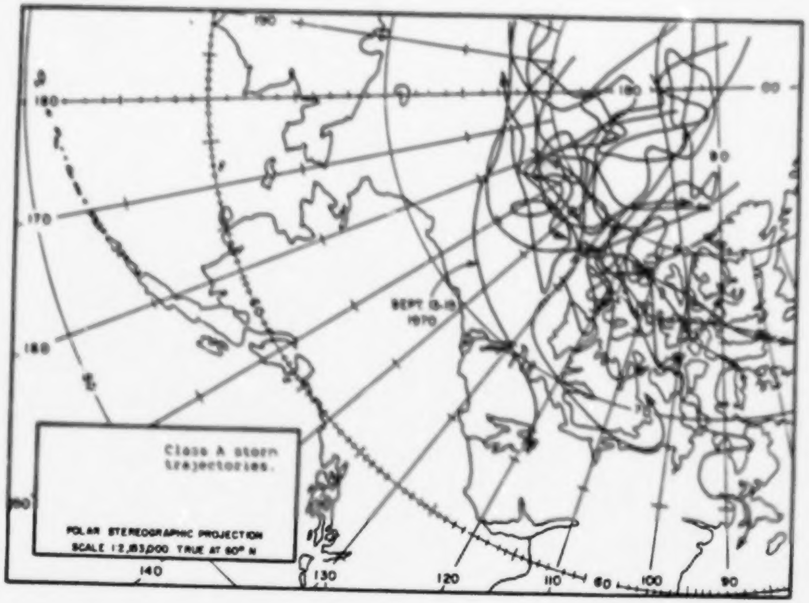
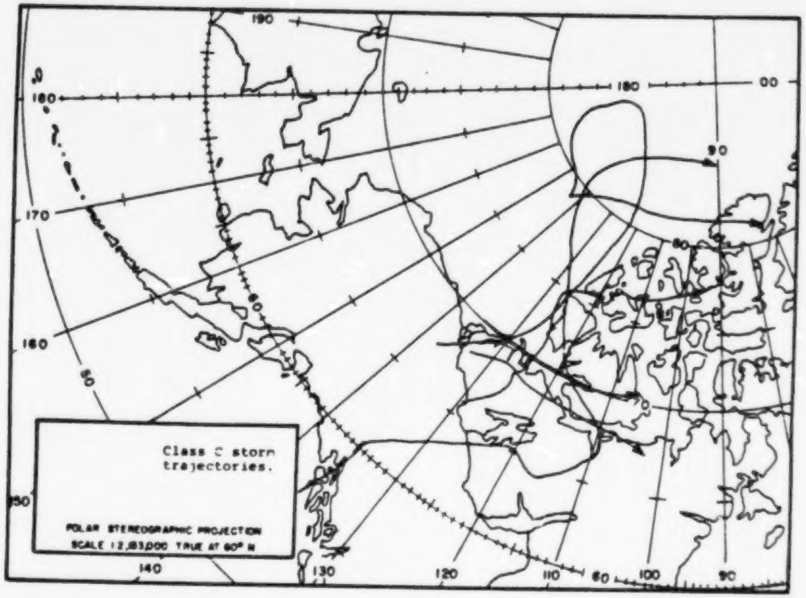

190
180
00
180
CLASS A
90
170
CLASS B
80
160
CLASS C
60
50
70
150
Severe storm trajectory routes for classification.
POLAR STEREOGRAPHIC PROJECTION
SCALE 1:2,153,000 TRUE AT 60° N
140
130
120
110
60
100
90

Figure 4.4 Storm classes based on trajectory routes.






Class C storm
trajectories.
POLAR STEREOGRAPHIC PROJECTION
SCALE 1:2,853,000 TRUE AT 60° N
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170
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100
90
80
60

Figure 4.5 Composite storm trajectories in each class. (Source: Hodgins and Harry, 1980).

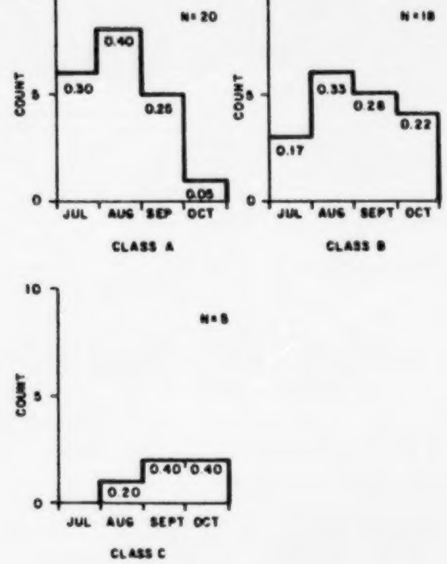


Figure 4.6 Storm distribution by class by month. (Source: Hodgins and Harry, 1982).

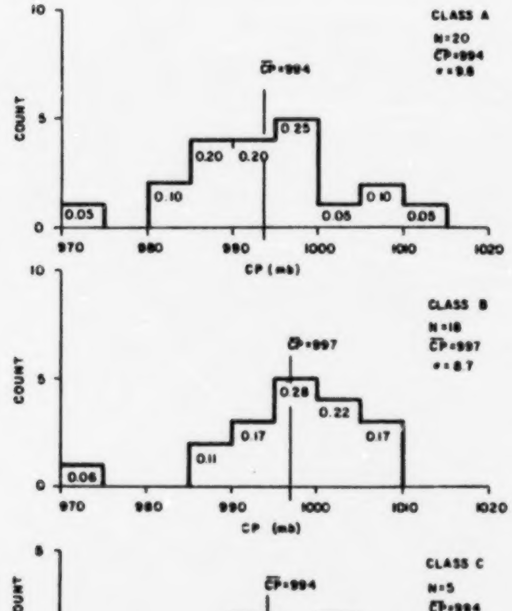


Figure 4.7 Distribution of central pressures by storm class. (Source: Hodgins and Harry, 1982).

was the best overall choice for synthesizing the long return period design storms.

4.2 Treatment of Sea Ice

The cumulative distributions for fetch length, as one parameter describing the extent of open water, were derived from 19 years of digital sea ice data compiled originally by the Ice Branch of AES (Markham, 1981). The data, distributed over the points shown in Figure 4.8, were obtained on magnetic tape and remapped onto a polar gnomonic projection of the Beaufort Sea. The following specifications pertain to the data:

years covered	1962 to 1980
season	June 18 to October 29
interval between maps	7 days
average spacing - AES points	55 km
pixel size - Seaconsult maps	10 x 17 km

A sample ice chart is shown in Figure 4.9 with the corresponding pixel map. These ice maps provided an easily read and interpreted history of the ice data over 19 summer seasons. Inspecting these maps provided the summary in Figure 4.10 of open water conditions delimited by the one-tenth ice edge. This figure indicates how much of the time very extensive open water conditions as modelled in the Seaconsult-1981 hindcast prevail and the distribution of these conditions in the 19 years of information.

As noted by Hodgins and Harry (1982), within the 19 year database, the hindcast conditions appeared for at least three consecutive weeks in 9 of those years and at least two consecutive weeks in 10 years. However, these data also showed large interannual variability in the number

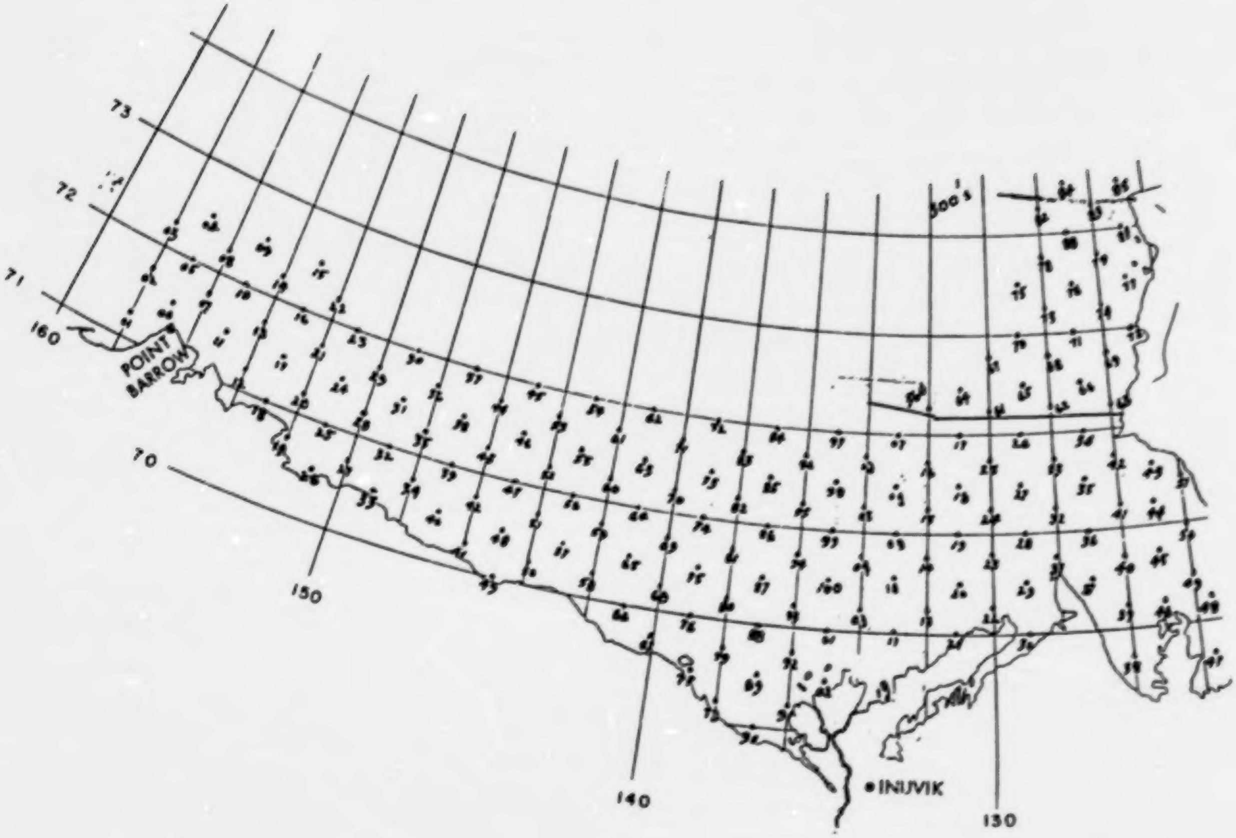


Figure 4.8 Ice digitization points used by Ice Branch of AES. (Source: Dr. W.E. Markham, AES).

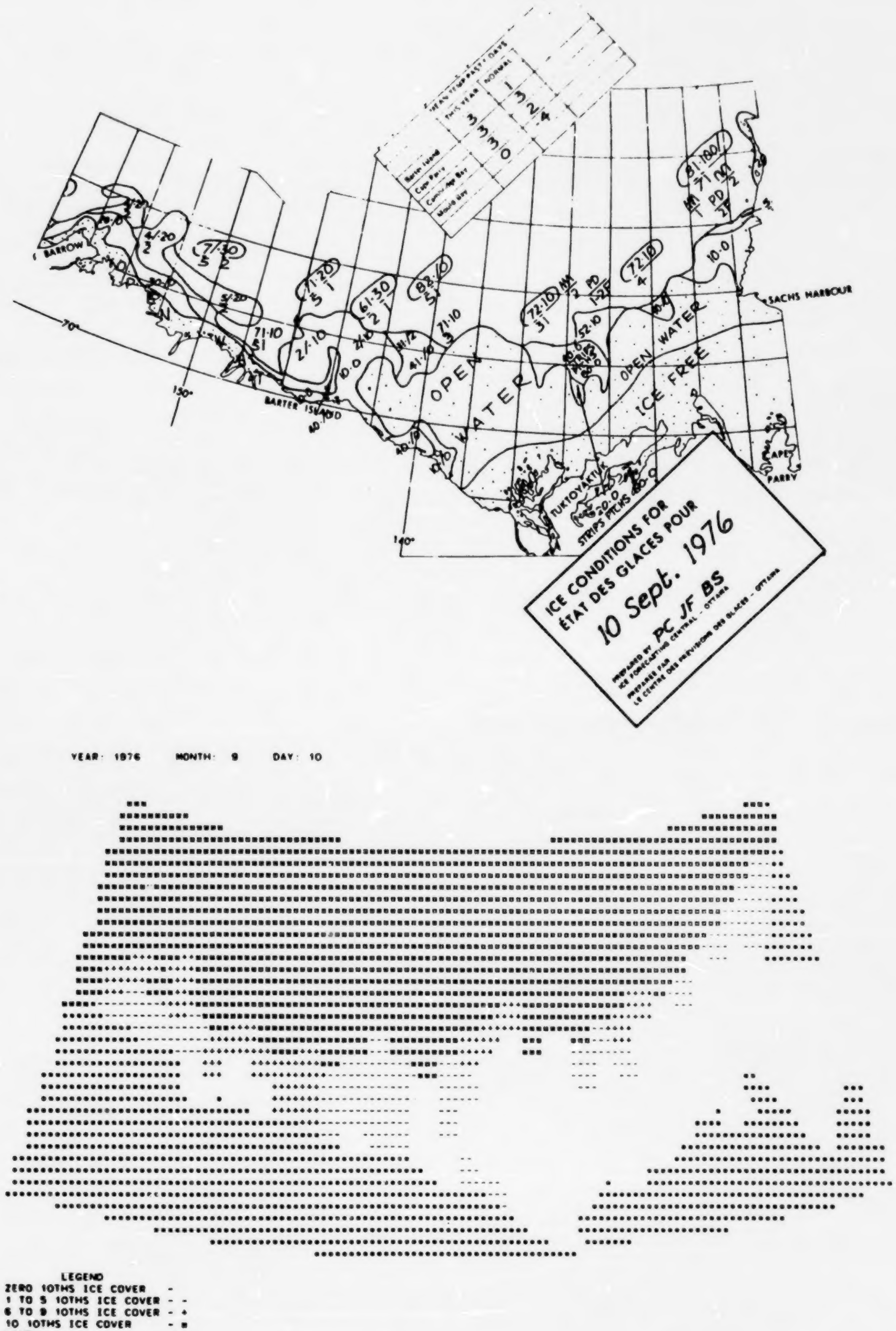
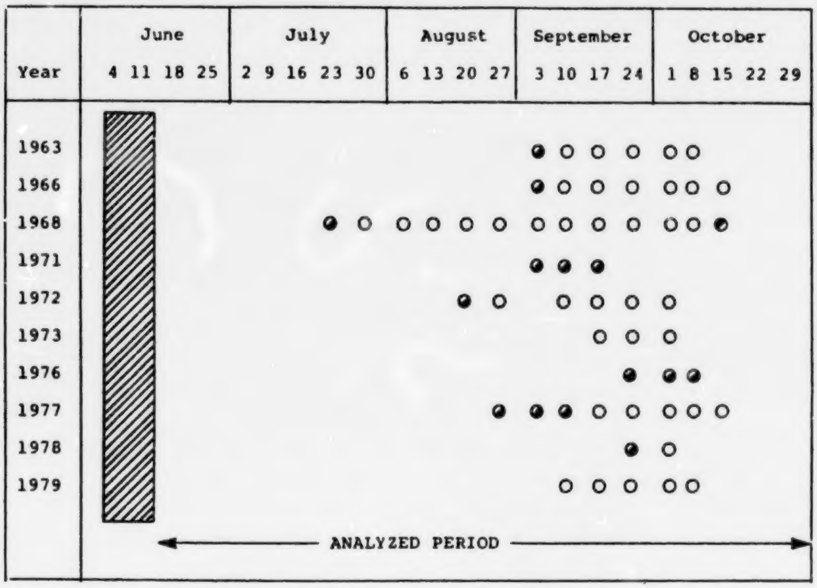


Figure 4.9 Sample 7-day summary ice chart (AES) and pixel map



○ - Open water for NW fetches greater than 1000 km

● - 1/10 - 5/10 ice cover at NW fetches greater than 650 km open water in between

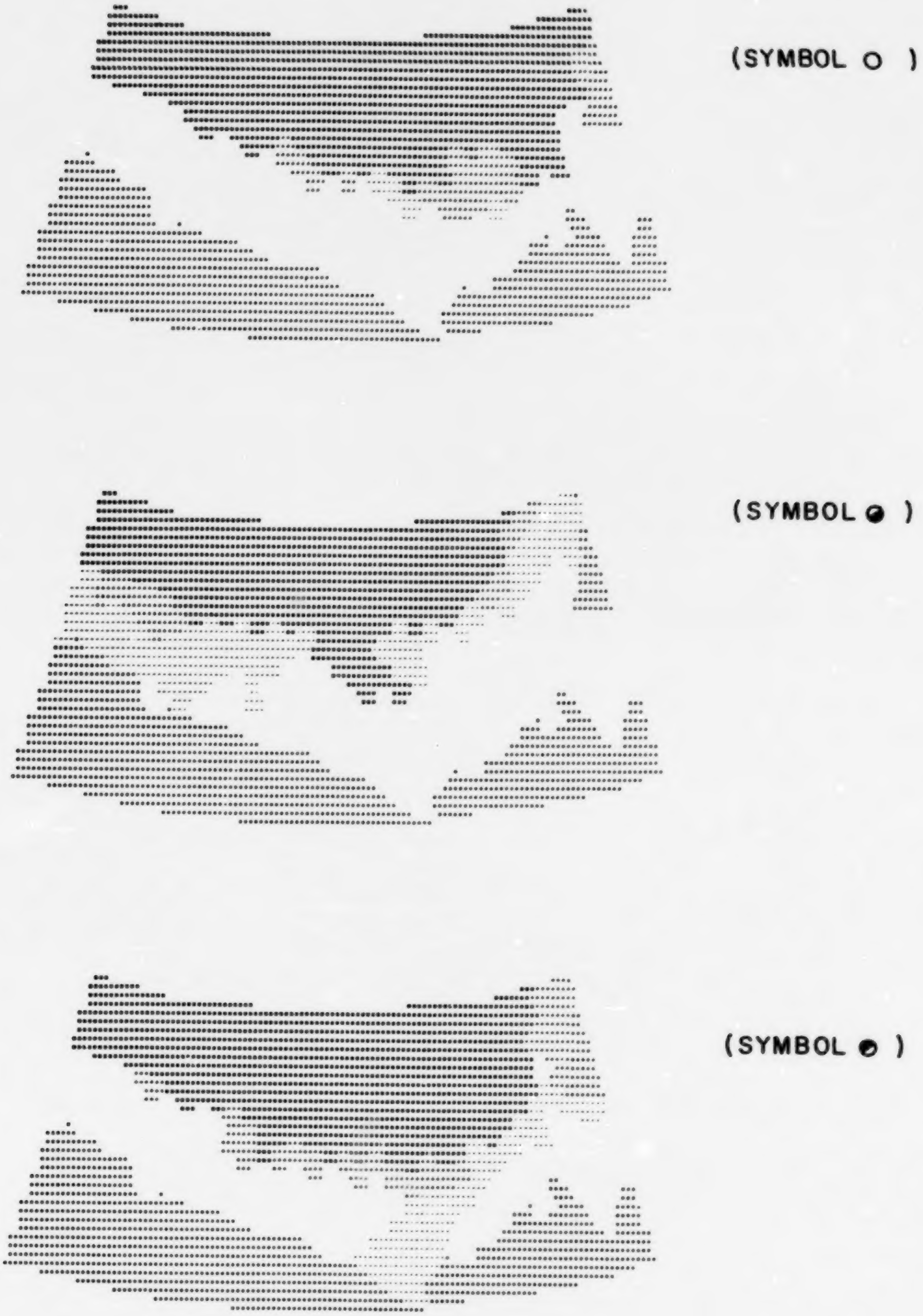
◐ - 1/10 - 5/10 ice cover near Mackenzie Bay sites, open water to NW up to fetches greater than 1000 km

total number of weeks for ○ = 41

total number of weeks for ○ + ● + ◐ = 56

(a)

Figure 4.10 Summary of extensive open water periods with potential for extreme wave generation (a). (Source: Hodgins and Harry, 1982). The meaning of the symbols is shown in Figure 4.10(b).



(b)

Figure 4.10 Continued.

of weeks within each season that these conditions were found, from a low of two to an extreme of 13--a rare season. The average number of weeks of extensive open water in the 10 years in Figure 4.10 is 5.6. They remark further that the data selection criteria for preparing this figure were strictly applied, so that in 1978 for example, the weeks preceding and following the two entries had very extensive fetches but not quite to the extent that was modelled by Seaconsult-1981.

Thus from August through October there were 247 weeks in the 19 years of data, of which 56 (23 percent) presented the required open water conditions. Considered on an average annual basis (i.e. three-month summer season) then the probability of occurrence is 0.23. Since the probability of the storm occurrence, say, with a 100-year return period is independent of the ice probability, then the wave conditions hindcasted by Seaconsult for this storm have a return period of about 400 to 500 years (1/(0.01 x 0.23) = 435 years).

To provide better temporal resolution within the summer season Hodgins and Harry (1982) computed the cumulative distributions for fetch length for the three points shown in Figure 4.11. The fetches were calculated as straight line distances (great circles on the polar gnomonic projection) on the ice maps for eight compass sectors, and the WNW azimuth in Figure 4.11.

The results are shown in bi-weekly periods in Figure 4.11 for the WNW fetch. These data show that the probability of long fetches is greatest during the last two weeks of September, but decreases rapidly in the first two weeks of October, particularly for fetches up to about 400 km long.

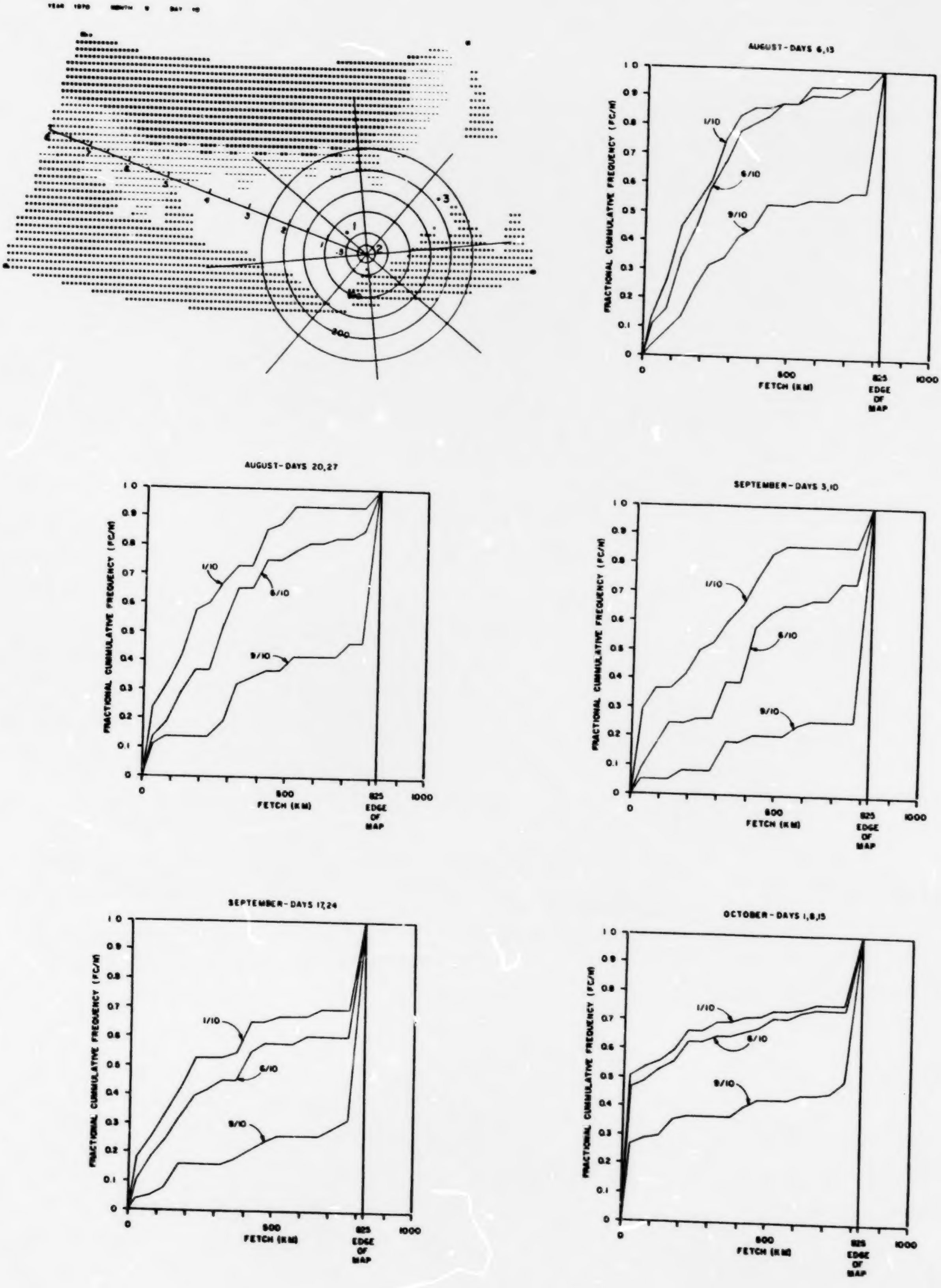


Figure 4.11 Cumulative fetch distributions for the WNW azimuth shown upper left.

4.3 Joint Probability of Extreme Wave Heights

The probability of occurrence data derived for fetches in bi-weekly periods were then combined with the storm wind distributions (MEP, 1982) to examine the joint probability of extreme wave heights. We recall that the storms used in the Seaconsult-1981 hindcast were derived by choosing a prototype storm, as modelled from the gridded pressure data, and then deepening the central low pressure to increase the gradients and consequently the cyclonic winds to yield a sequence of design storms. The yardstick used to gauge their intensity was the set of extreme winds in Mackenzie Bay predicted from 10 years of summer maxima. When the peak wind in the design storm matched that from the statistical treatment of these maxima the return period was established. Because of this procedure Hodgins and Harry (1982) argue that the storm duration is not a parameter independent of the wind speed; the duration of winds at any reference level automatically increases as a consequence of deepening the low. This can be clearly seen in Figure 2.24.

It would be desirable to have a measure of storm intensity that incorporates both wind speed and duration. Once the distribution of this intensity parameter is established the return period of storms in a particular class (i.e. the class to which the intensity applies) can then be determined. In practical terms this type of parameter is difficult to define although the 12-hour averaged wind speed might be a reasonable choice. Now in terms of the Beaufort Sea data:

- two storm classes were identified, of about equal severity with a probability of 1 for an occurrence each summer season;

- one wind speed distribution, based on all classes, was available to gauge the intensity of a design storm selected from one class; and
- the fetch distributions for a WNW direction were known.

Only one design storm, out of Class B, was hindcasted in the Seaconsult-1981 study, but in terms of severe waves, storms of both Classes A and B must be considered. Therefore in view of the above conditions an approximate expression for the joint wave height probability was given as

$$P_r(H_s) = P_r(S) \cdot P_r(U>U_{ref}) \cdot P_r(F>F_{ref}) \qquad (4.1)$$

where

$P_r(S)$ = probability of a storm in either Class A or Class B occurring,

$P_r(U>U_{ref})$ = probability of winds in a storm of Class A or Class B occurring with speeds greater than a certain reference speed,

$P_r(F>F_{ref})$ = probability of a WNW fetch greater than a certain reference length.

Here $P_r(S)$ is calculated as the sum of the individual probabilities of Class A or B storms occurring in bi-weekly periods.

Equation (4.1) was applied with the Beaufort Sea data as follows. The storm probabilites $P_r(S)$ were known from the trajectory analysis. For illustrative purposes it was assumed that all trajectories shown in Figure 4.5 (A and B Classes) would be equally effective in generating severe sea states. This is a conservative assumption (giving a large H_s) based on the idea that wave heights in Mackenzie Bay are not too sensitive to the precise location of the "low"; this could obviously be refined in an extension of this design storm selection process. The $P_r(F>F_{ref})$ was also known from the marginal distributions for fetch (Figure 4.11). The reference fetch was then chosen by, in effect, selecting the desired sea-state conditions; in their case Hodgins and Harry (1982) looked at duration-limited wave heights. The reference fetch for these exceeds 500 km. (Clearly, the fetch to give duration-limited wave heights depends on the wind speed and so the process is an iterative one.) The bi-weekly probabilities were then scaled from the marginal distributions.

The solution of (4.1) was given for a specified joint probability of H_s, i.e.

$$P_r(U>U_{ref}) = \frac{P_r(H_s)}{P_r(S)\cdot P_r(F>F_{ref})} \tag{4.2}$$

yielding the probability (return period) of the storm required to give the specified wave conditions--duration-limited with say, a 50 or 100-year return period. Having found the storm (intensity) then the hindcasted wave conditions corresponding to it were the appropriate conditions for $P_r(H_s)$.

By way of an example, in the last two weeks of September the probability of storms would be:

in Class A	0.17
in Class B	0.33
together	0.50

neglecting July events in the trajectory classification. With $P_r(F>500 \text{ km}) = 0.42$ and $P_r(H_s) = 0.01$,

$$P_r(U>U_{ref}) = 0.048 \text{ (return period} \sim 21 \text{ years)}$$

Therefore the design storm having about a 20-year return period is required. This corresponds very roughly with Seaconsult's E1 storm (Figure 2.23) for which $H_s \approx 8$ to 9 m offshore of the Tuktoyaktuk Peninsula (sites 6 and 7 in Figure 2.19).

Hodgins and Harry (1982) are careful to point out that this example only illustrates the effect of considering ice together with storm winds on the hindcasted wave heights. They do not replace the Seaconsult-1981 hindcast values with new results derived in the later study, but clearly a downward adjustment of the wave heights is warranted.

A number of improvements to the data used in this process for determining the design storm for specified conditions are desirable:

- using a more representative measure of storm intensity than peak hourly-averaged wind,
- deriving distributions of storm intensity for each class of storm,
- selecting storm trajectories in each class based on sensitivity of hindcasted wave heights to position of the design storm low, and
- improving the quality of the design storms in terms of temporal and spatial wind field resolution.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 The Situation Now

Five major hindcast studies have been carried out for the Beaufort Sea providing data from which 50 and 100-year return period wave heights were estimated. A sixth estimate (Brower et al., 1977) is judged to be unreliable due to the inappropriate use of Thom's (1973b) probability distribution for wave heights. The other five estimates as published in the study reports vary widely, for reasons discussed in Chapter 2 of this report. Three of these five were parametric wave hindcasts based on SMB procedures. Of these the Hydrotechnology-1980 study was judged to be the most reliable because

- it used the apparent best source of overwater winds (Tuktoyaktuk measurements scaled by transfer functions derived from overwater measurements at drilling sites), and
- it applied the SMB hindcasting procedures in the most rigorous fashion of the three studies.

However, each of the parametric studies derived the extreme wave heights by statistically extrapolating the hindcasted annual (three-month summer season) maximum heights, assuming the joint probability distribution for wave heights was modelled by FT-I or FT-II functional forms. The independent marginal distributions for wind speed (and duration) and ice-governed fetch were not explicitly considered in this process.

When results from each of these parametric studies were placed on a comparable footing and fitted with an FT-I distribution they yielded H_s (100-year) estimates ranging from 5.5 to 6.5 m in deep water off Mackenzie Bay despite large differences in year-by-year hindcast results. So, while confidence in the Hydrotechnology results is limited because the hindcast incorporated only nine seasons, it is not clear that extending the procedures to more years would alter the estimates by a statistically significant amount.

The Hydrotechnology-1980 procedures are also the best verified of the parametric modelling methods. Nevertheless, the hindcast modelling was carried out for all nine entire open water seasons because climatological wave data were required in addition to storm maxima. The verification examined only the overall fit of the data in four years and no attempts were made to calibrate the model for specific storms. In many high-wave cases in the data presented by Baird and Hall (1980) the model predictions do not correspond with measurements as well as would normally be considered acceptable for storm-based hindcasts. This also limits confidence in the extreme wave estimates. It was clearly recognized that in some instances the wind field variability produced the poor fit to observations. Thus any improvement in the procedures must upgrade the overwater wind field data, and this is probably more important than including additional years of data using the same approach for deriving winds.

The Seaconsult-1981 hindcast attempted to deal with the spatial variability in both the wind fields and the marginal ice zone. It used a design storm approach where the wind fields were modelled every 3 hours by intensifying a prototype storm. This reference storm was derived initially from 381-km gridded pressure data using a machine-based procedure implemented by MEP

(1982). This procedure did not involve blending direct wind observations into the pressure-derived wind fields. Wind verification trials subsequently showed that

- the pressure data often provided inadequate resolution of some severe weather systems, in particular of rapid changes in wind speed associated with fronts; and
- some small-scale but very intense storms were not represented in the pressure database at all and could not be modelled.

An important consequence of the first conclusion was the smoothing out of temporal variations in the prototype design storm. This resulted in long durations of strong winds and rather severe wave conditions. Because the ice position used in the Seaconsult-1981 study was taken at its furthest distance offshore the extreme wave heights have longer return periods than the design storms from which they were derived. A later study by Hodgins and Harry (1982) examined the influence of seasonal ice distributions on the extreme wave height estimates and concluded that roughly a 30 percent reduction in the values reported earlier by Hodgins et al. (1981) was warranted. This would place H_s (100-year) in the 8 to 9 metre range in deep water off Mackenzie Bay.

Based then on the Hydrotechnology-1980 hindcast and the Seaconsult-1981 and later results, estimates of extreme wind speeds and wave heights can be given within the following ranges:

	Return Period (Years)	
	50	100
hourly-averaged wind (knots) Mackenzie Bay	55 to 56	59 to 60
deep water significant wave height (m)	6 to 8	7 to 9

These values are applicable to the hatched area shown in Figure 5.1. The shaded portion of this figure indicates the area where waves with periods greater than 10 s will be affected by the bathymetry. To derive extreme wave heights in this region the deep water heights will require modification for refraction, shoaling and dissipation (see e.g. the review presented by Hodgins et al., 1983). In practical terms, however, more than a 10 percent change in wave height due to shoaling is confined to water less than 10 m deep for wave periods of about 10 to 12 s. Also strong refraction in Mackenzie Bay takes place in water shallower than about 40 m (Dames and Moore, 1975).

5.2 Obtaining Improved Hindcasts

The principal limitation on past hindcasts is the modelling of overwater winds. Improved hindcasts will need to incorporate the spatial and temporal variations present in observed wind fields, and take advantage of two-dimensional wind wave models to translate the wind information accurately into wave data. At present the use of Tuktoyaktuk, or other near-shore measurements, to generate uniform overwater winds is a workable approximation, consistent with parametric wave height (SMB) models. However, the SMB technique does not resolve the spatial structure of either storm wind fields or the marginal ice zone, and so will not provide a route to improved wave modelling.

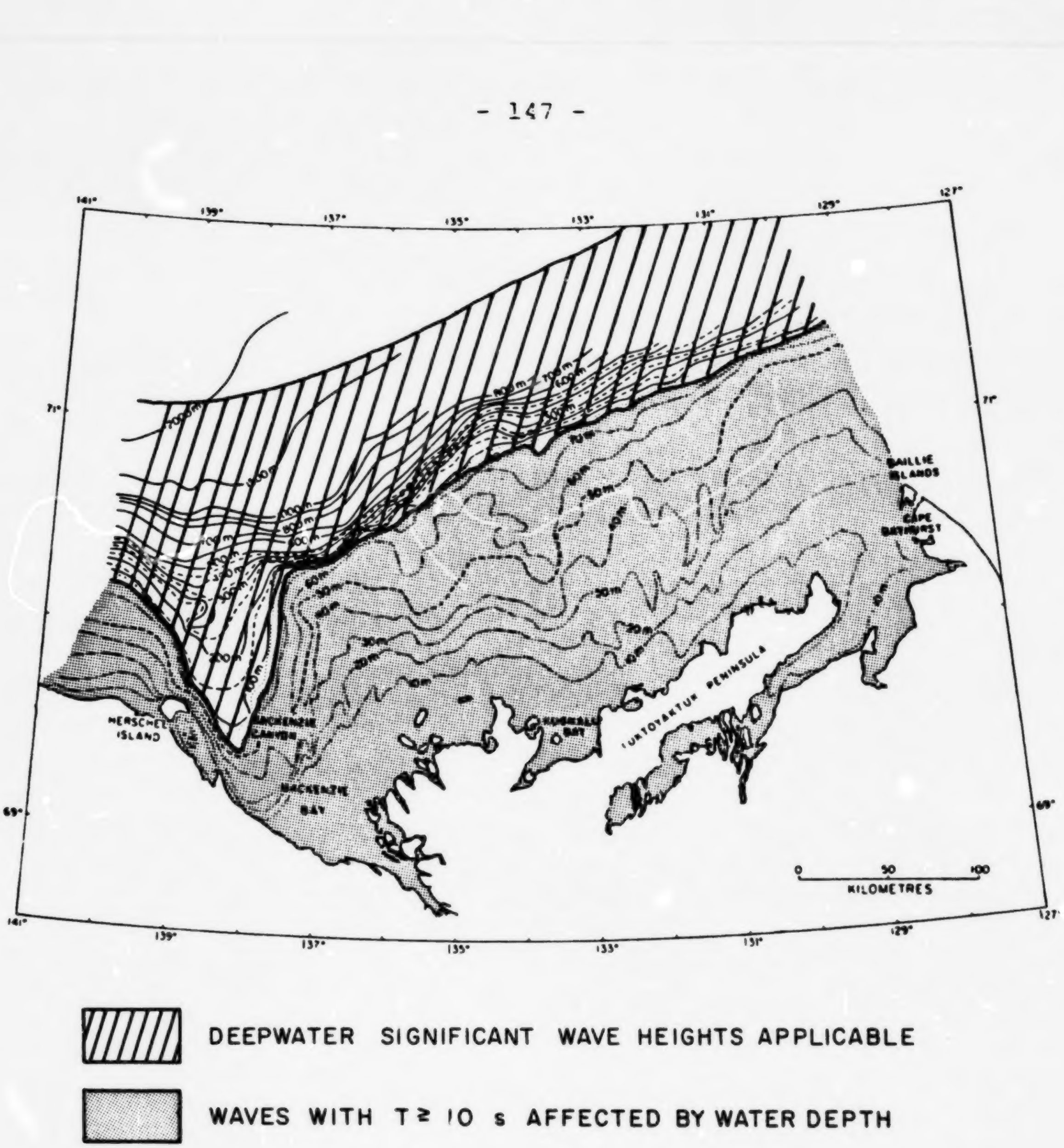


Figure 5.1 Map of the Beaufort Sea showing areas of deepwater and depth-modified wave conditions.

The greatest difficulty in constructing two-dimensional storm wind fields over the Beaufort Sea appears to be the lack of reporting stations distributed over water and ice areas, especially in the past but even today. This also implies that the meteorological analysis charts are inherently less accurate than, for example, the coastal Atlantic and Pacific regions. This latter aspect may be more true for charts compiled before satellite imagery was available than since. Nevertheless it affects the design of a hindcast study because it will be difficult to work back in time selecting severe storms and then deriving wind fields for them by blending geostrophic winds, reduced to sea level, with observed winds (see e.g. Moores et al., 1976; Cardone et al., 1979 for a discussion of methods).

In fact, because adequate data coverage is in many respects confined to the last decade, the design storm approach has some definite advantages. It permits the selection of events in each class of storms that are (relatively) well monitored. This allows the prototype storms to be described in terms of, say, 3-hourly two-dimensional wind fields that contain the motion of fronts over the area, using all data (pressure charts, imagery, direct wind measurements and air temperature and humidity data) which are known with confidence.

Of course the intensification of the storms to a lower probability of occurrence than the observed prototype system requires some considerable degree of meteorological judgment, assuming one has a scale of intensity for the class of storms. This scale may in fact be the hardest aspect of the procedure to establish. Nevertheless, the design storm approach allows the hindcast team to judge the physical reasonableness of the low probability events, it takes full advantage of the resolving power of two-dimensional discrete spectral wave models, and the influence of the marginal distributions for ice-restricted fetch can be incorporated explicitly in determining the 50 or 100-year wave heights.

For the design storm approach the classification by trajectory examined by Hodgins and Harry (1982) could form the basis for deriving the event probabilities; however, the following improvements would be warranted:

- extending the number of years analyzed for storms,
- refining the definition of storm intensity in each class, and
- better relating the trajectories to the generation of severe sea-states in the area of interest.

Two additional aspects must be considered when viewing improvements to hindcast procedures. Both parametric and spectral models are based on measurements in ice-free waters but it is the spectral models, which predict the rate of growth of wave energy as a function of wave frequency, that will be more sensitive to the extent of low concentration ice cover. Research has been conducted into the decay of energy as waves propagate into increasingly heavier ice (Robin, 1963; Wadhams, 1973; Squire and Moore, 1980; Wadhams and Squire, 1980) but to the author's knowledge no work has been done on wave growth in the presence of sea ice. If hindcasting results prove to be sensitive to the unconsolidated ice, lack of detail on the historical ice charts will make ice parameterization impossible, and in that case the hindcasting of historical storms cannot be improved. The problem of ice is discussed further in the next section.

The second aspect concerns the modelling of shallow water effects on wave spectra and heights. Current practice is to calculate wave heights and periods in deep water and modify these shoreward using engineering refraction and shoaling calculations. However, incorporating refraction, shoaling and dissipative processes into spectral models will be required for improved hindcasting in Mackenzie Bay and along the coastline of the Tuktoyaktuk Peninsula. Presently, there are no directional spectral data available in shallow water to verify the results of such spectral modelling. These data would be required as part of an overall program to upgrade hindcasting, and forecasting procedures.

It was noted in Chapter 2 that very few of the hindcast techniques were verified against instrumental data collected during severe storms. Questionable judgment on the part of the hindcasters aside, Chapter 3 detailed some serious limitations in the Waverider database which restrict the level of verification which can be undertaken. Thus there is a continuing need for high quality instrumental wave data in the Beaufort Sea since it can be used to identify deficiencies (such as omission of Arctic instability lows) in the wind data as well as to judge the performance of wave hindcasting models given adequate wind input.

5.3 Longer Term Research Needs

It is argued in the last section that improved hindcasting in the Beaufort Sea requires better definition of severe storm events and the use of two dimensional spectral models. There are three areas where research needs can be identified:

- meteorological data,
- sea ice data and wind wave growth,
- shallow-water wave modelling and supporting wave data.

(a) Meteorological Data

In terms of the historical data what is presently available is limited by lack of reporting stations. There is no opportunity to augment these data and their analysis for storm events will have to rely on sound meteorological analysis and judgments, familiarity with the Beaufort Sea and, perhaps, wind modelling techniques. In terms of improving storm definition in the future, however, an expanded network of reporting stations giving better spatial coverage than presently available from the exploratory drilling sites is essential. Ideally the coverage should extend 200 to 400 km offshore, onto the permanent ice cover, and further westward to the International Boundary. A cooperative program with American agencies along the Alaskan coast, using satellite reporting stations and ensuring central data archiving would also be valuable because of the tendency of some severe weather systems to track parallel to the coastline.

While clearly beneficial to forecasting operations, these data would be used to better understand storm systems from the hindcasting perspective. The benefit for the design storm approach is that by blending measured winds at many points on more than one side of the central low, a verified time history of prototype system wind fields may be obtained.

(b) Wave Growth in Sea Ice

Discrete spectral models contain frequency dependent growth, decay and non-linear wave-wave interaction formulations. Some models such as the System 20 used in the Seaconsult-1981 hindcast, limit wave growth by a saturation spectrum over the whole frequency range, and all models assume a parametric energy fall-off in the high frequency range, usually proportional to f^{-5}. All of these formulations were derived for ice-free waters where the high frequency components, in particular, were free to receive energy from the wind or from redistribution processes within the spectrum unimpeded by floating ice. In the presence of floe ice, it is well known that the high frequency components are rapidly attenuated compared with the longer waves (Wadhams, 1973), and so it is reasonable to expect that growth and decay processes would be modified from those observed in ice-free waters. In terms of the spectral models this could require a change in the calibration coefficients governing these processes, in the saturated spectral shape, in the formulation of energy sink terms (decay terms) and in the spreading functions for energy about the mean wind direction.

Presently unknown aspects are:

- the way in which sea ice modifies the physics of wave growth and decay,

- the methods of specifying this in operational wind wave models, and

- how serious a problem this actually is for hindcasting in the Beaufort Sea.

Answers to these questions will require some quite fundamental research in the Beaufort Sea.

(c) Shallow Water Wave Modelling

As shown in Figure 5.1 a large percentage of the shelf area in the southern Beaufort Sea is capable of modifying extreme waves as they propagate shoreward. Depth refraction, shoaling and dissipation processes due to bottom effects are not routinely included in discrete spectral models. In fact, these are very complex phenomena which require good data down to small scales for accurate results. The problems associated with modelling these processes are discussed by Hodgins et al. (1983), in terms of their basic physics, as it is understood now, and in terms of modelling strategies. Implementing a spectral wave model, or set of models, to give site specific extreme wave data in the Beaufort Sea must be regarded as a longer term research goal.

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